CHAPTER 19

Eye movements and on-line comprehension processes

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19.1 Introduction

Reading is a rather complex process in which comprehension at a number of levels is essential. In this chapter, we will provide an overview of how different kinds of variable influence eye movements. We want to stress at the outset that eye movement data are highly informative with respect to understanding reading. They provide a moment-to-moment indicator of the ease (or the difficulty) with which readers are able to comprehend the text that they read. Because eye movements are a natural part of the reading process, secondary tasks are not needed to make inferences about reading comprehension. Rather, information about where readers fixate in the text and how long they look at different part of the text provides remarkably reliable data about comprehension at a number of levels.

We will begin with a brief overview of the characteristics of eye movements during reading, which will include a discussion of the different eye movement measures that are typically employed in reading research (these issues are discussed in greater detail in Rayner, 1998, and in Rayner and Pollatsek, forthcoming). We will then discuss in turn: (1) effects of lexical processing on eye movements, (2) effects of syntactic processing on eye movements, and (3) effects of discourse processing on eye movements. Thus, these sections focus on comprehension at the word level, at the level of syntax, and at the level of higher-level discourse. Shillcock (Chapter 6 this volume) also discusses eye movements and word recognition.

19.2 Basic characteristics of eye movements during reading

On the basis of introspection, it can appear that the eyes move smoothly across the text as one reads. In fact, the eyes move in a series of jumps, remaining relatively stationary between these jumps. The jumps, known as "saccades," typically require 20–40 ms. The durations of the stationary periods, known as "fixations," comprise a somewhat right-skewed normal distribution with the mean at around 200–250 ms and minimum and maximum at about 50–100 ms and about 500 ms, respectively. Meaningful information is extracted from the text only during fixations; during saccades, the visual system does not register the information picked up by the retina.

In normal English reading, the eyes move about 7–9 letter spaces on the average saccade. However, there is great variability in saccade size, with some saccades ranging over twenty characters, and others moving the reader's eyes by only a single character. In skilled readers, about ninety per cent of saccades move the eyes forward, with the rest moving the eyes backward in the text, either to resolve comprehension difficulty or to correct error in the programming of forward saccades (these backward eye movements are known as "regressions"). How many fixations a reader makes on a word is, unsurprisingly, related to a word's length, and very short words are frequently skipped altogether (Brysbaert and Vitu, 1998; Rayner and McConkie, 1976).

Function words such as determiners and prepositions, which tend to be quite short, are in fact skipped more than half of the time (Carpenter and Just, 1983; Rayner and Duffy, 1988).

Based on the anatomy of the eye, it is possible to divide the text that is visible on each fixation into three regions. The "foveal" region consists of the text within about 1° of visual angle on either side of the fixation point; at a normal viewing distance, this is about 3–4 letters to the left and right of fixation. Beyond this region, visual acuity drops off rapidly, but readers are still able to obtain some letter identity information in the "parafoveal" region, which extends up to about 5° of visual angle to either side of the fixation point. Beyond the parafovea, in "peripheral" vision, readers are usually only aware of the general shape of the text, such as where a line ends.

Interestingly, the area of text from which readers obtain useful information is not symmetric. Studies that have carefully controlled the amount of text the reader can see (e.g. McConkie and Rayner, 1975; Rayner and Bertera, 1979) have shown that for readers of English, this region extends 14–15 character spaces to the right of fixation, but only 3–4 characters to the left. Given the limits of visual acuity, the region in which readers can actually identify words (the "perceptual span") extends only 7–8 characters to the right of fixation, though this varies as a function of text difficulty. It has also been shown that readers do not make use of information from the lines of text below the one they are fixating (Pollatsek et al., 1993). Readers of languages in which a great deal of information is conveyed by each character (e.g. Chinese) have a considerably smaller perceptual span, one character to the left of fixation to 2–3 characters to the right when reading from left to right (Inhoff and Liu, 1998); readers of languages that are read right to left (e.g. Hebrew) have a span that is larger to the left of fixation than to the right (Pollatsek et al., 1981). These findings show that the size and shape of the perceptual span are in fact determined by complex attentional and information-processing factors, not just by perceptual limitations.

It is clear from the foregoing discussion that on a given fixation, a reader of English is likely to obtain useful word identity information primarily about the word that is currently being fixated and the word immediately to the right of this word. Experiments that have manipulated the visibility of the word to the right of fixation (so-called "boundary change" experiments; Rayner, 1975) have shown that readers do indeed obtain useful information about this word, and that in fact this word is typically read 30–40 ms faster when it was visible on the previous fixation than when it was not (Hyönä et al., 1998; Rayner, 1998). Many studies have explored the nature of the information that the reader extracts about the word to the right of fixation; it appears that readers generally have access to information about the specific letters in this word (Briihl and Inhoff, 1995; Inhoff et al., 1987; Johnson, forthcoming; Johnson et al., forthcoming; Rayner et al., 1980; Rayner et al., 1982) and about the phonological or sound codes in the word (Ashby and Clifton, 2005; Ashby and Rayner, 2004; Ashby et al., 2006; Chace et al., 2005; Henderson et al., 1995; Miellet and Sparrow, 2004; Pollatsek et al., 1992; Sparrow and Miellet, 2002). On the other hand, neither information about a word's meaning (Altarriba et al., 2001; Rayner et al., 1986) nor information about the word's morphological composition (Inhoff, 1989; Kambe, 2004; Lima, 1987) is usually available before the word is fixated directly.

As noted above, short words tend to be skipped more frequently. This may be partly because short words are more likely to be identified while the eyes are still fixated on the previous word. This explanation is consistent with results showing that words are also skipped more often when they are easy to identify either because they are predictable in context (Gautier et al., 2000; Rayner and Well, 1996) or because they are very frequent (Rayner et al., 1996). (We have more to say below on the role of these lexical factors in controlling eye movements.) Interestingly, the duration of the fixation prior to a skip is inflated (Drieghe et al., 2005; Kliegl and Engbert, 2005; Pollatsek et al., 1986; Pynte et al., 2004).

Though linguistic factors clearly play a role in word skipping, in general it seems that low-level visual information is the most important input to decisions about where to move the eyes. Rayner and Pollatsek (1981) conducted an experiment in which the amount of text that the reader could see varied randomly from fixation to fixation, and found that the less text was visible to the right of fixation, the shorter the reader's saccades. Subsequent research has shown that the spaces between words are of primary importance (Morris et al., 1990; Pollatsek and Rayner, 1982; Rayner, Fischer, and Pollatsek, 1998), with readers tending to make their first fixation on a word between the beginning and middle of the word (McConkie et al., 1988; Rayner, 1979; Rayner et al., 1996), and using the information provided by spaces to execute a saccade of the appropriate length. Interestingly, when the initial fixation on a word is near the beginning or end of the word, it tends to be relatively short (Vitu et al., 2001). Nuthmann et al. (2005) have recently demonstrated that this is largely because these fixations reflect errors in saccade programming that the reader rapidly corrects.

Compared to decisions about *where* to move the eyes next, decisions about *when* to move the eyes (or, looked at another way, decisions about how long to remain focused on a given point in the text before moving on) are quite strongly affected by cognitive factors related to text comprehension. It is these factors that are the focus of the remaining sections of this chapter. The fact that such cognitive processes are of great importance in these *when* decisions is perhaps demonstrated most clearly by the experimental finding that when each word disappears as soon as 50–60 ms after it is first fixated, reading proceeds quite normally (Ishida and Ikeda, 1989; Rayner et al., 1981), with fixation durations still being affected by factors such as word frequency (Liversedge et al., 2004; Rayner, Liversedge, and White, 2006; Rayner et al., 2003). In other words, most of the time devoted to each fixation is not needed for low-level perceptual processing, but is instead used for higher-level linguistic or conceptual processing.

Given that fixation duration is more sensitive than saccade length to linguistic factors, it is not surprising that the most commonly used measures of processing difficulty in psycholinguistic studies are temporal measures (though probability of skipping a word and regressing to it are typically also reported). In studies in which the critical region of text is a single target word, the measures most often used are "first fixation duration" (the duration of the first fixation on the word), "single fixation duration" (the time spent on a word on those trials on which only a single fixation was made on the word), and "gaze duration" (the sum of the durations of all fixations on the word before leaving the word). In addition, "total time" on the word (the time spent on the word including re-reading) is often reported, as is "go-past time," also known as "regression path duration" (the time from first fixating the word to first moving past the word to the right, including time spent in rereading earlier parts of the sentence). Less frequently, "second pass time" (the time spent rereading the word) is also reported. When larger regions of text are being examined, the first fixation duration is often not a meaningful measure, but the other measures mentioned above are all commonly reported (though when a region comprises multiple words, the term "first pass time" is used instead of gaze duration). With multiple-word regions, researchers also frequently report the percentage of trials on which readers made a regressive eye movement out of the region on their first pass through the region. On occasion they also report the percentage of trials on which readers made a regressive eye movement *into* the region.

Measures such as first fixation duration and gaze duration/first pass time are often referred to as "early" measures, while total time and second pass time are "late" measures. While it is important to define, in a given theoretical context, exactly what is meant by this distinction (see Clifton et al., 2006), careful examination of the point in the eye movement record at which the effect of some linguistic manipulation first appears can be highly informative about the nature of the underlying cognitive processes involved.

This brings us to a final issue introduced by Just and Carpenter (1980), referred to as the "eye–mind span": how big of a lag is there between the eyes and the mind. When we read out loud, if the lights in the room are turned off, we are still able to produce two or three words after the lights go out. This is because there is an eye–voice span where the eyes are ahead of the voice by a few words. Analogously, is there an eye–mind span where the eyes are ahead of the mental processing associated with each word, or is the link rather tight? As we'll see in the next section, there is quite a bit of evidence that various lexical properties of a word influence the amount of time that the eyes remain on that word. The link isn't perfect, as there are preview effects (i.e. when readers have a valid preview of the next word to the right of fixation, they look at it for about 30–50 ms less time than if they have no preview of the word) and spillover effects (i.e. the processing associated with a given word can sometimes spillover onto the next word in the text). But, it is generally the case that how long readers look at a word is a fairly good reflection of the processing time associated with that word.

19.3 **Effects of lexical processing on eye movements**

In this section we review how eye movements in reading are affected by properties of individual words. This general topic can be divided fairly naturally into two subtopics. First, we discuss the role of factors such as frequency, morphology, and lexical ambiguity, which we call "intrinsic" lexical factors. We then discuss how the fit between a word and its context influences eye movements, under the heading of "relational" lexical factors.

19.3.1 Intrinsic lexical factors

Rayner (1977) and Just and Carpenter (1980) first reported that readers look longer at words that are used relatively infrequently. Not surprisingly, frequency is confounded with word length; however, Rayner and Duffy (1986) and Inhoff and Rayner (1986) controlled for differences in word length, and found that there was still a strong frequency effect both on the first fixation on a word and on gaze duration. These basic findings have now been replicated many times (see Rayner, 1998; Reichle et al., 2003 for summaries). In addition, high-frequency words are skipped more often (O'Regan, 1979; Rayner et al., 1996), and reading time on the word after a low-frequency word is inflated (Rayner and Duffy, 1986). However, reading time on a low-frequency word decreases dramatically when it is repeated in a text (Rayner et al., 1995).

Word frequency is determined by counting the occurrences of a word in a corpus of printed or spoken materials, but word familiarity is determined by a norming procedure in which participants rate how familiar they are with a given word. Familiarity has an effect on reading time that is independent of frequency (Chaffin et al., 2001; Juhasz and Rayner, 2003; Williams and Morris, 2004). Age of acquisition (Juhasz, 2005), which is determined by both corpus counts and subjective ratings, also has an independent effect (Juhasz and Rayner, 2003; 2006).

Recently, several studies have examined effects of the morphological structure of a word on reading time. Studies of long and morphologically complex Finnish words (Hyönä and Pollatsek, 1998; Pollatsek and Hyönä, 2005; Pollatsek et al., 2000) have demonstrated that the frequency of the first morpheme (and, to a lesser extent, the second morpheme) in a two-morpheme word influences fixation durations, suggesting that these words are decomposed into their constituent morphemes as they are analyzed. Interestingly, this is true both of transparent compound words, in which the meaning of the whole is systematically related to the meaning of the parts, and of opaque ones. Morphological decomposition has also been demonstrated in English (Andrews et al., 2004; Juhasz et al., 2003).

Another word-intrinsic factor that has a significant influence on fixation times is meaning ambiguity (Rayner and Duffy, 1986; Duffy et al., 1988; Rayner and Frazier, 1989; Sereno et al., 2006). When a word has two meanings that are approximately equal in frequency, and the word is encountered in a neutral context, fixation durations are inflated compared to an unambiguous control word matched on length and overall frequency. If the word has one dominant meaning, on the other hand, there is no increase in reading time; evidently, competition from the subordinate meaning does not slow processing. Not surprisingly, if information later in the sentence reveals the subordinate meaning to be the relevant one, disruption appears in the form of long fixations and regressive eye movements. When disambiguating information precedes a balanced ambiguous word, reading time on the word is no longer inflated, compared to an unambiguous control; but when preceding information disambiguates a biased ambiguous word toward the subordinate meaning, reading time on the word is increased (this is known as the "subordinate bias effect"). Rayner et al. (2006) have shown that even a single biasing adjective preceding a target noun can produce this effect. However, Folk and Morris (2003) found that the subordinate bias effect disappears when the two meanings of a word are in different syntactic categories (e.g. *rose*), and only one of these categories provides a syntactically legal continuation of the sentence.

Other forms of ambiguity result in distinct patterns in the eye movement record. Frazier and Rayner (1987) found that when a word is ambiguous between two syntactic categories, and either category could appear in the sentence context (e.g. the word *trains* could be either a noun or a verb in the sentence *I know that the desert trains*…), slowdown does not appear on the ambiguous word itself, but only later in the sentence (see also Pickering and Frisson, 2001). Similarly, Frazier and Rayner (1990) found that when a word has two senses, rather than two distinct meanings (e.g. the word *newspaper* can refer either to a physical object or to an institution), there is no slowdown on the word itself. On the other hand, fixation durations are increased when a single spelling corresponds to two distinct, and differently pronounced, words (e.g. *tear*; Carpenter and Daneman, 1981; Folk, 1999), and when a word is a homonym of a more frequent word (e.g. *chute/shoot*; Jared et al., 1999; Rayner, Pollatsek, and Binder, 1998). In sum, it seems likely that fixation times are increased when an ambiguity results in competition between alternative lexical representations, though the nature of the mechanisms underlying these various effects is under debate.

19.3.2 Relational lexical factors

A considerable body of research has demonstrated that reading time decreases as the predictability of a word, based on the preceding context, increases. Predictability (also called "contextual constraint") is usually defined in terms of Cloze probability, which is the probability that informants will produce the target word as the likely next word in the sentence, given the sentence up to that point. Ehrlich and Rayner (1981) first demonstrated the effect of predictability on reading time, and this effect has now been confirmed many times (Ashby et al., 2005; Balota et al., 1985; Frisson et al., 2005; Rayner, Ashby, et al., 2004; Rayner and Well, 1996). Readers are also more likely to skip words that are highly predictable in context. Recently, it has also been reported (MacDonald and Shillcock, 2003a; 2003b) that the transitional probability between two words, based on corpus counts, has an independent effect on reading time on the second word. However, subsequent work (Frisson et al., 2005) has suggested that when overall predictability is well controlled, transitional probability may not have an independent effect.

Fixation durations on a word are also affected by semantic priming from a specific preceding word (or words). Morris (1994) reported shorter first fixation and gaze durations on a target word that was semantically associated with a preceding word in the sentence, even though the target word was not predictable; e.g. on the word *moustache* in the sentence *The friend talked to the barber and trimmed the moustache after lunch* (cf. Carroll and Slowiaczek, 1986, who argued that the associate must be within the same clause in order for semantic priming to have an effect on fixation times). Morris and Folk (1998) reported that this facilitation depends in part on whether the semantic associate of the target word is in linguistic focus.

At the extreme low end of the predictability continuum are cases in which the target word does not even make sense in its context. Several studies have examined how readers process such semantic anomalies. Though the processing of anomalies is probably not directly informative about normal reading, it does help to reveal the time course with which meaning-related factors influence eye movements. At least three studies (Braze et al., 2002; Murray and Rowan, 1998; Rayner, Warren, et al., 2004) have found that when a word is implausible given the preceding context, first fixation or gaze duration on the word is inflated. The study by Rayner, Warren, et al. (2004) suggests, however, that the processing of semantic anomaly is not a unitary phenomenon. Rayner et al. reported increased gaze duration on the direct object when it was essentially an impossible theme for the verb (e.g. *carrots* in *John used a pump to inflate the large carrots for dinner*) but only a go-past effect on this word when it was an implausible theme given the combination of verb and instrument (e.g. *John used an axe to chop the large carrots for dinner*), coupled with a first pass effect on the next region. Anomaly never significantly increased the first fixation on the word, leading Rayner et al. to conclude that this early measure reflects primarily lexical processing itself, rather than higher-level integrative processing.

Finally, several studies have reported that specific kinds of semantic processing have measurable effects on reading time. Traxler, McElree, et al. (2005) and Traxler et al. (2002) investigated the effect on readers' eye movements when the context forces a noun with no intrinsic temporal component to be interpreted as an event, as in the phrase *finish the book*, and found increased go-past time on the critical word or increased first pass time on the next region (see also Frisson and Pickering, 1999). Frisson and Frazier (2005) found that when a mass noun appears with plural morphology (e.g. *some beers*) or a count noun appears in the singular with a plural determiner (e.g. *some banana*), there is an increase in the duration of the first fixation on the critical word.

Summing up this section, we point out that recent models of eye movement control in reading (e.g. E-Z Reader: Pollatsek et al., 2006; Reichle et al., 1998; Reichle et al., 2006; Reichle et al., 2003, and SWIFT: Engbert et al., 2005) have accounted for a large portion of the variance in fixation durations by focusing exclusively on the kinds of lexical factor discussed above. Specifically, it appears that in addition to word length, frequency and predictability are especially good predictors of the amount of time the eyes will spend on a word. However, a very large literature has now demonstrated that some kinds of higher-level linguistic factors can also exert a strong influence. The next two sections are devoted to a discussion of these factors.

19.4 Effects of syntactic processing on eye movements

It is clear from several decades of psycholinguistic research that as a sentence is read, the reader constructs an analysis of the sentence's syntactic structure in a highly incremental manner, usually on a word-by-word basis (Frazier and Rayner, 1982; Just and Carpenter, 1980; see Pickering, 1999 for discussion). In this section we focus on the question of how this process of incremental syntactic analysis affects eye movements in reading.

In most experiments examining the effects of syntactic processing on eye movements, participants read sentences that are temporarily ambiguous between two syntactic structures. In sentence (1) below, for example, the region in italics could initially be analyzed either as part of the subordinate clause or as the subject of the main clause:

(1) Since Jay always jogs *a mile and a half* seems like a very short distance to him. (Frazier and Rayner, 1982).

In light of the findings reviewed in the last section, an obvious question is whether syntactic ambiguity has an effect similar to lexical ambiguity. Does the presence of two possible syntactic analyses result in slower reading times, similar to the manner in which reading times are slowed when an individual word has two meanings that are roughly similar in frequency? A second question is how a reader's eye movements are affected when subsequent material reveals that the reader's initial analysis of a syntactic ambiguity is incorrect. If, for example, a reader initially analyzes the ambiguous region of (1) as part of the subordinate clause, what happens when the reader encounters the word *seems*, since this word cannot be attached into the sentence on this analysis?

Of the very large number of published eye movement studies dealing with syntactic ambiguity (approximately seventy, according to a recent review by Clifton et al., 2006), the vast majority have not reported any statistically significant effects on reading time in the ambiguous region itself. A small number of studies (Frazier and Rayner, 1982; Traxler et al., 1998; van Gompel et al., 2005; van Gompel et al., 2001) reported experiments in which an ambiguous region was in fact read more quickly than the corresponding region of an unambiguous control sentence. Three of these (Traxler et al., 1998; van Gompel et al., 2001; van Gompel et al., 2005) were explicit attempts to answer the question of whether competition between multiple syntactic analyses results in slower processing (e.g. MacDonald et al., 1994; McRae et al., 1998), so it is worth discussing their results in some detail. Traxler et al. (1998) compared reading times for sentences like the following:

(2a) The driver of the car with the moustache was pretty cool.
(2b) The car of the driver with the moustache was pretty cool.
(2c) The son of the driver with the moustache was pretty cool.

Sentence (2c) is globally ambiguous: it is never clear whether the prepositional phrase *with the moustache* is a modifier of the first noun phrase (*the son*) or the second noun phrase (*the driver*). Across three experiments, Traxler et al. found that gaze duration on the word *moustache* was shorter in condition (c) than in conditions (a) or (b). van Gompel et al. (2005) demonstrated a similar effect for attachment of adverbial phrases. They tested sentences like (3a–c):

(3a) The carpenter sanded the shelves he will attach onto the kitchen wall yesterday morning …
(3b) The carpenter will sand the shelves he attached onto the kitchen wall yesterday morning …
(3c) The carpenter sanded the shelves he attached onto the kitchen wall yesterday morning …

Sentence (3c) is again globally ambiguous, since *yesterday morning* could modify either the first verb (*sanded*) or the second one (*attached*). This phrase must modify the first verb in (3a), and the second in (3b). The adverbial phrase or the next region was read faster in (3c) than in (3a) or (3b).

A few studies have also reported a slowdown in the ambiguous region compared to an unambiguous control (Clifton et al., 2003; Kennison, 2001; Ni et al., 1996; Paterson et al., 1999; Schmauder and Egan, 1998). However, an explanation other than ambiguity is often available. For example, Clifton et al. (2003) examined sentences like (4a, b):

(4a) The ransom paid by the parents was unreasonable.
(4b) The ransom that was paid by the parents was unreasonable.

Clifton et al. found longer first fixation durations on the verb (*paid*) in sentences like (4a), in which this verb could be either the main verb of the sentence or the beginning of a relative clause, than in (4b), in which this verb is unambiguously part of a relative clause. However, when participants were reading under normal conditions (there was also a condition in which the amount of visible text was restricted), this effect was due almost entirely to those sentences in which the subject was inanimate. In these sentences, the normally preferred main verb analysis (on which e.g. the ransom is paying somebody or something) is implausible, so readers may have taken longer to read this verb in (4a) because they had to revise their initial analysis at this point. In another study on the reduced relative/main verb ambiguity, Ni et al. (1996) found slower reading times on the relative clause verb when it was morphologically ambiguous (e.g. *raced*) than when it was an unambiguous passive participle (e.g. *ridden*). However, these verb forms were not equated for other factors known to affect reading times.

In sum, there are very few, if any, solid experimental results indicating that syntactic ambiguity causes a slowdown in reading, and there seem to be circumstances in which ambiguity leads to especially fast reading times. Evidently readers either do not consider multiple syntactic analyses in parallel (Frazier, 1978; 1987), or if they do, competition between these analyses does not disrupt processing (van Gompel et al., 2001; 2005). This conclusion stands in contrast with the conclusion from studies of the processing of lexical ambiguity, in which it has been clearly shown that competition between multiple word meanings does slow reading times.

Research using other paradigms has sometimes revealed apparent effects of syntactic ambiguity on on-line processing (e.g. Fiebach et al., 2004; Frisch et al., 2002; Stowe et al., 2004). Frisch et al. (2002) conducted an event-related potential (ERP) experiment with German readers in which the P600 waveform (which is usually associated with syntactic processing difficulty) appeared when a sentence-initial noun phrase was ambiguous between subject and object. Fiebach et al. (2004) and Stowe et al. (2004) both report distinct patterns of brain activation associated with the processing of syntactic ambiguity in functional magnetic resonance imaging (fMRI) studies. However, we think that several methodological issues need to be addressed before drawing theoretical conclusions on the basis of these results. In all these studies, sentences were presented to participants in a segmented manner at an extremely slow rate, with at least 500 ms between word onsets. In the ERP experiment, each participant saw a total of 160 sentences, of which 80 had an ambiguous initial noun phrase, raising the possibility that participants became aware of the experimental manipulation and adopted task-specific strategies. In the fMRI experiments, the observed increase in activation could only be approximately time-locked to the ambiguity itself. In sum, more research is needed to determine the theoretical significance of these findings from other paradigms.

In most studies of syntactic effects on eye movements, the primary focus is the region of a sentence that resolves a temporary ambiguity. The logic of these studies is simple: if normal reading is disrupted when a reader reaches this material (in the form of longer reading times, more regressive eye movements, or both) it is reasonable to infer that this disambiguating material is inconsistent with the reader's initial syntactic analysis. In other words, the reader has been "garden-pathed" (Bever, 1970). In this way, the eye movement record provides a tool for uncovering the parser's initial structural choices.

The first study to examine systematically the effect on eye movements when an initial syntactic analysis is disconfirmed was by Frazier and Rayner (1982; see also Rayner and Frazier, 1987). They examined ambiguities like that in (1) above, as well as ambiguities like that in (5):

(5) The second wife will claim the entire family inheritance belongs to her.

As the reader progresses through this sentence, *the entire family inheritance* could initially be analyzed either as the direct object of *claim* or as the subject of an embedded clause. Upon reaching the verb *belongs*, it becomes clear that the latter analysis is the correct one. Abstracting away from the details of the analyses, what Frazier and Rayner found was that the very first fixation on the disambiguating region was lengthened in sentences like (1) and (5), compared to control sentences in which the correct analysis was signaled earlier in the sentence. This disruption persisted for several fixations, and readers were also more likely to make regressive eye movements to earlier regions of the sentence.

Rapidly appearing effects of syntactic disambiguation have also been shown when this disambiguation takes the form of implausibility, rather than ungrammaticality. In another early study, Rayner et al. (1983) tested sentences like (6a, b):

(6a) The kid hit the girl with a whip before he got off the subway.
(6b) The kid hit the girl with a wart before he got off the subway.

They found increased first pass reading time beginning with the word *wart* in sentences like (6b), where this word indicates that the prepositional phrase is not a plausible argument or modifier of the verb. This suggests that readers' initial parsing preference is indeed to attach the prepositional phrase to the verb, rather than to the noun that is the verb's direct object.

Eye movement experiments have now been used to investigate the parser's preferred analysis of many types of temporary ambiguity; an extensive list of references organized by the type of ambiguity under investigation appears in Clifton et al. (2006). Because there are reliable signs of disruption in the eye movement record when an initial syntactic analysis is disconfirmed, researchers have been able to test subtle and linguistically sophisticated hypotheses about the strategies and principles that the parser employs. For example, eye movement experiments have helped to reveal that the parser adopts a very "eager" strategy for resolving so-called long-distance dependencies, in which a phrase appears some distance from the element from which it gets its thematic role, as in a question like *Which boy did the teacher reward?*, where *which boy* is the theme of the verb *reward* (Pickering and Traxler, 2001; 2003; Traxler and Pickering, 1996). They have also helped to reveal that the processor is sensitive to a phrase's status as an argument or adjunct of a verb, and prefers to attach incoming material as an argument (Clifton et al., 1991; Kennison, 2002; Liversedge et al., 1998; Liversedge et al., 2003; Speer and Clifton, 1998).

A central question for parsing theories is whether factors such as plausibility, appropriateness in context, and lexical preferences play a role in determining the initial analysis that the parser constructs (e.g. MacDonald et al., 1994; Trueswell et al., 1994), or whether this initial analysis is constructed entirely on the basis of structural preferences (e.g. Ferreira and Clifton, 1986; Frazier, 1987), with other factors affecting only a later stage of processing (Binder et al., 2001; Frazier et al., 2006; Rayner et al., 1992). For example, Ferreira and Clifton (1986), Trueswell et al. (1994), and Clifton et al. (2003) have all conducted eye movement studies of the processing of sentences like (4a, b) above, with the goal of determining whether there is a brief period during which the parser's structural preferences lead it to adopt the implausible main verb analysis of sentences like (4a), in which, for example, the ransom is paying someone or something. In this chapter we will not attempt to settle the substantive question of whether the parser does in fact adopt such an analysis, since a review of the relevant evidence would constitute a chapter in itself. Instead, we merely point out that questions about the fine details of the time course of syntactic analysis are most likely to be settled by eye tracking experiments, in contrast to, say, self-paced reading (see Mitchell, 2004 for discussion). In the latter paradigm, participants must press a button to reveal each new word or phrase, resulting in unnaturally slow reading times (often 400–600 ms per word). This may make it difficult, if not impossible, to determine exactly when a particular factor has its effect, and it may be impossible to detect real, if short-lived, syntactic misanalyses. Because ERP experiments can reveal fine temporal details of brain activity in response to syntactic manipulations, they are likely to be useful in this regard, though in this paradigm as well the stimulus is usually presented at a very slow rate that does not approximate real-world uptake of either written or spoken language.

We note that there are continuing questions about the details of the relationship between eye movements and syntactic disambiguation. For example, it is unclear whether disruption due to disconfirmation of an initial syntactic analysis generally results in movement upwards of the entire reading time distribution, or whether it sometimes affects only a subset of trials, but affects these to such a great extent that the overall differences between conditions are statistically significant (see Clifton et al., 2006 for discussion of this issue). There are also open questions about the circumstances under which disambiguation results in a slowing down of forward saccades, regressive eye movements, or both (Altmann, 1994; Altmann et al., 1992; Rayner and Sereno, 1994a; 1994b). However, both Frazier and Rayner (1982) and Meseguer et al. (2002) have presented evidence that when readers do make regressive eye movements, they do not do so randomly. Instead, the landing position of these regressions reflects some awareness of the point at which the reader's initial, incorrect analysis diverged from the correct analysis.

Not all experiments examining the effects of syntactic processing on eye movements have employed syntactic ambiguities. Several articles have focused on the time-course with which grammatical information affects eye movements by studying the effects of syntactic anomaly (Braze et al., 2002; Deutsch and Bentin, 2001; Ni et al., 1998; Pearlmutter et al., 1999). For example, Pearlmutter et al. (1999) had participants read sentences in which the verb either did or did not agree with the subject (*key* in (7) below) in number. In addition, an irrelevant noun that intervened between the subject and the verb could either agree with the verb or not:

(7) The key to the cabinet/cabinets was/were rusty from many years of disuse.

Pearlmutter et al. found that on the word following the verb, ungrammaticality and mismatch in number with the irrelevant distractor resulted in an approximately equal increase in gaze duration. Surprisingly, the manipulations had no effect on the verb itself, except in late measures such as total reading time. Deutsch and Bentin (2001), on the other hand, found that when the gender of the verb in Hebrew sentences explicitly mismatched the gender of the subject, there was a first pass effect on the verb itself. Sturt (2003) also found that when an anaphor (*himself*, *herself*) did not match the stereotypical gender of its antecedent, this increased the duration of the very first fixation on the anaphor. Clearly, more research is required in order to understand the processing principles underlying these apparently conflicting results.

There are additional questions about the relationship between syntactic processing and eye movements which have received relatively little investigation. One question is whether syntactic complexity has an effect on reading time, in the absence of ambiguity (e.g. Hyönä and Vainio, 2001). Does a sentence take longer to read if its structure is syntactically complex, as measured by, for example, the number of nodes in the sentence's phrase structure diagram? Another question is whether constraints related to working memory have an effect on syntactic processing. While research from other paradigms such as self-paced reading (see Gibson, 1998 for discussion), speed–accuracy tradeoff (McElree et al., 2003), and ERP (Fiebach et al., 2002; Kaan et al., 2000; Vos et al., 2001) suggests that syntactic processing is influenced by memory load, very few eyetracking studies have focused specifically on this issue (though see Traxler et al., 2005). Still another question is whether syntactic effects on eye movements interact with lower-level effects (e.g. lexical frequency and predictability effects), or whether these are two independent sources of variability in the eye movement record. Finally, a question that we have recently begun to investigate in our own laboratory is whether reading is speeded when a sentence's structure can be predicted in advance (see also Altmann et al., 1998). For example, we have recently found (Staub and Clifton, 2006; Staub et al., 2006) that the presence of the word *either* significantly speeds reading of coordinate structures that make use of the word *or*, even in the absence of ambiguity, and that a direct object that appears to the right of its usual position adjacent to the verb is read more quickly when the verb is obligatorily transitive (e.g. *John praised from the stands his daughter's attempt to shoot a basket*) than when the verb is optionally transitive (e.g. *John watched from the stands his daughter's attempt to shoot a basket*).

Finally, an additional interesting finding, which has been replicated on several occasions (Just and Carpenter, 1980; Rayner et al., 2000; Rayner et al., 1989), is that fixation durations on a word are inflated when the word ends a clause or sentence. Because the sentences in these experiments are typically identical through the target word (with the only difference being whether additional material follows this word), it is likely that this extra reading time is due to integrative processing that takes place at clause and sentence boundaries. Rayner et al. (2000; see also Hill and Murray, 2000) found, however, that readers tended to make longer saccades following these extended fixations on sentence- and clause-final words. This suggests that once readers have completed their integrative processing, it is as if they have emptied a buffer and now have extra processing resources available. Hirotani et al. (2006) have also recently demonstrated that implicit prosody (i.e. sentence phrasing and intonation) plays a role in these wrap-up effects, though this prosody is actually imposed by the reader.

19.5 **Effects of discourse processing on eye movements**

In order to comprehend a text, the reader must not only recognize individual words and analyze the grammatical structure of each sentence; he or she must also maintain a representation of the entities and events that have been mentioned, and relate the information that is currently being processed to this stored representation. This involves, for example, determining which entities pronouns (e.g. *she*) and definite descriptions (e.g. *the fisherman*) refer to. It also involves making inferences about relationships between events and entities, including explanatory, causal, and chronological relationships. Compared to the large number of eye movement studies of syntactic parsing, relatively few studies have examined how such discourse processing affects eye movements in reading; we suspect that this may be a growth area in the next several years. In this section, we review the literature that now exists.

In ordinary spoken language, an anaphoric element such as a pronoun or a reflexive typically has an antecedent. Blanchard (1987) found that the process of identifying this antecedent could be so easy that it left no trace in the eye movement record. However, it is now clear that if the antecedent violates a gender stereotype (e.g. if the reflexive *herself* refers to *the pilot*), reading time on the pronoun is inflated (Duffy and Keir, 2004; Sturt, 2003; Sturt and Lombardo, 2005). In addition, the distance between an anaphor and its antecedent influences fixation times; when the antecedent is relatively far back in the text, fixations on the pronoun, as well as the next few fixations, tend to be longer (Ehrlich and Rayner, 1983; Garrod et al., 1994; O'Brien et al., 1997). Fixation times are also inflated when the antecedent is a low-frequency word (van Gompel and Majid, 2004). Albrecht and Clifton (1998) and Moxey et al. (2004) also demonstrated increased reading time on a pronoun when it refers to one member of a conjoined NP (e.g. *John and Mary painted the room. He really liked the color*), and Moxey et al. found that reading time on the plural pronoun *they* was reduced when the reference was a conjoined NP.

Though it is sometimes felicitous to use a definite description without specifying an antecedent (which is essentially never the case with a pronoun or reflexive), it appears that readers also identify antecedents for definite descriptions on-line, and that doing so carries some processing cost. Duffy and Rayner (1990) found evidence of increased reading time on a definite description when the antecedent was distant (though unlike the case with anaphors, this effect was localized to the NP itself; see also van Gompel and Majid, 2004).

Establishing the referent of a pronoun or definite NP can be seen as a form of inference. A potentially more difficult, but no less common, form of inference takes place when readers draw conclusions that have not been explicitly stated in the text. Eye movement experiments have shown that when readers make such "elaborative" inferences, processing is slowed. O'Brien et al. (1988) had participants read passages followed by a critical sentence in which a target word appeared. An example is shown below; the target word is *knife*:

(8) He threw the knife into the bushes, took her money, and ran away.

The preceding passage could explicitly mention a knife (*he stabbed her with his knife*), strongly suggest the existence of a knife (*he stabbed her with his weapon*), or make only rather general reference to a category of which a knife is but one exemplar (*he assaulted her with his weapon*). Gaze duration on the target word did not differ between the first two conditions, but was longer in the third condition. Evidently, in this last condition readers needed time to complete the inference that the weapon mentioned earlier in the passage was in fact a knife. However, O'Brien et al. also found that such an inference tended to be made only when a sentence preceding the target sentence invited one, and a follow-up study by Garrod et al. (1990) found evidence for such inferences only when the target noun co-referred with a preceding noun. Myers et al. (2000) also found that when a category name was introduced in one sentence and an exemplar of the category was introduced in a later sentence, both the typicality of the exemplar and the distance between the two words influenced fixation times. Other studies (Cook and Myers, 2004; Garrod and Terras, 2000) have found that a target word is read more quickly when it fills a thematic role that is left open in the preceding discourse; for example, if the preceding sentence makes reference to *driving*, the word *car* would be read particularly quickly.

19.6 Summary

In this chapter, we have provided a brief review of issues and studies related to on-line comprehension processes. As we pointed out earlier, it is fairly clear that variables related to lexical processing (such as frequency, age of acquisition, and predictability) have a major impact on eye movements, and particularly the decision of when to move the eyes. Models of eye movement control in reading (Engbert et al., 2005; McDonald et al., 2005; Pollatsek et al., 2006; Reichle et al., 1998; Reichle et al., 2003; Reichle et al., 2006; Reilly and Radach, 2006) do a fairly good job of accounting for how such variables influence eye movements and how the decision is made concerning where to move the eyes next. But, as should be clear from our review, higher-level syntactic and discourse level variables also influence eye movements. Current models do not do a good job of accounting for the impact of these variables on decisions about when and where to move the eyes.

In fact, a reasonable account of eye movements in reading would be to suggest that lexical variables are the primary engine driving the eyes through text (and they primarily influence fixation times), and that higher-level variables typically (though not always) exert their influence later in processing. Thus, the higher-level variables may primarily serve to slow down processing (and increase fixation times) when something doesn't compute well (as in the case with garden path effects, anomaly effects, and when a discourse referent is difficult to locate). Future research and further modeling work is needed to more fully explicate exactly when and how these higher order variables exert their influence.

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