Eye Movements in Reading Words and Sentences

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Abstract

Word recognition processes seem to be reflected quite straightforwardly in the eye movement record. In contrast, eye movements seem to reflect sentence comprehension processes in a more varied fashion. We briefly review the major word identification factors that affect eye movements and describe the role these eye movement phenomena have played in developing theories of eye movements in reading. We tabulate and summarize one hundred reports of how syntactic, semantic, pragmatic, and world-knowledge factors affect eye movements during reading in an initial attempt to identify order in how different types of challenges to comprehension are reflected in eye movements.

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Readers move their eyes through a text in order to acquire information about its content. Measurements of the duration and location of the fixations they make have taught researchers a great deal about how people acquire information from the printed text, how they represent it, and how they integrate it in the course of understanding a text (see Rayner, 1978, 1998, for extensive overviews). Much of the systematic variance in fixation duration and location can be attributed to processes of recognizing the individual words in the text. Understanding of the relation between word recognition and eye movements has progressed to the point where several formal and implemented models of eye movements exist. Many of these models are described in detail, as well as compared and evaluated, by Reichle, Rayner, and Pollatsek (2003; more recent descriptions of new or updated models can be found in Engbert, Nuthmann, Richter, & Kliegl, 2005; Feng, 2006; McDonald, Carpenter, & Shillcock, 2005; Pollatsek, Reichle, & Rayner, 2006; Reichle, Pollatsek, & Rayner, 2006; Reilly & Radach, 2006; Yang, 2006). In our opinion, the most successful models are those that link the word recognition process to the time when an eye moves from one fixation to the next and the target of the saccade that accomplishes this movement. Our favored model, the E-Z Reader model (Pollatsek et al., 2006; Rayner, Ashby, Pollatsek, & Rayner, 2004; Reichle, Pollatsek, Fisher, & Rayner, 1998; Reichle, Rayner, & Pollatsek, 1999) predicts a large proportion of the variance in eye movement measures on the basis of variables whose effect on word recognition has been independently established.

Despite their success, word recognition-based models of eye movement control do not yet provide fully satisfactory answers about all aspects of eye movements during reading. In the E-Z Reader model, a distinction that is made between two phases of recognizing a word (which are assumed to control different aspects of programming a saccade and the shifting of attention) has been criticized as being not fully-compelling (see the replies to Reichle et al., 2003). No model fully specifies the nature of the mental representations of words (e.g., their orthographic or phonological or morphological content) nor does any model fully specify how information that specifies these different representations is acquired foveally versus parafoveally. No model fully specifies how the sequence in which orthographic symbols appear in a printed word is mentally represented. And, even though it has been clear at least since Frazier and Rayner (1982; Rayner, Carlson, & Frazier, 1983) that higher-level factors such as syntactic parsing and semantic integration can influence fixation durations and eye movements, no existing model adequately accounts for their effects.

In the first section of this chapter, we will briefly review some of the well-understood effects of word recognition on eye movements and comment on the extensions of these effects that are discussed in the chapters that appear in the Eye Tracking and Reading section of this volume. In the next section, we go on to analyze the effects of syntactic, semantic, and pragmatic factors on eye movements, and discuss one basis of the difficulty of modeling, namely the apparently-variable way that these factors find expression in eye movements. We begin this section with a discussion of one case study of how different measurements of eye movements can provide very different pictures of how some high-level factors influence reading and language comprehension (Clifton, 2003). We continue with an extensive survey of published articles that investigate the effects of high-level factors on eye movements, attempting to find some order in what kinds of effects appear in which measures of eye movements.

Word recognition and eye movements

Perhaps the two most robust findings in studies of eye movements and reading are that (1) fixation time on a word is shorter if the reader has a valid preview of the word prior to fixating it, and (2) fixation time is shorter when the word is easy to identify and understand. The chapters in this section largely deal with these two issues. Johnson's chapter provides further information regarding the specifics of preview information and demonstrates (see also Johnson, Perea, & Rayner, 2006) that transposed letters are more efficient previews than substituted letters. This result indicates that specific letter identities (probably converted into abstract letter codes) are important in preview benefit. Bertram and Hyönä's chapter deals with the extent to which morphological information from Finnish words can be processed parafoveally. Consistent with research on English (Kambe, 2004; Inhoff, 1989; Lima, 1987), they find little evidence for morphological preview benefit. Interestingly, research on Hebrew has demonstrated morphological preview benefits (Deutsch, Frost, Pollatsek, & Rayner, 2000, 2005; Deutsch, Frost, Peleg, Pollatsek, & Rayner, 2003). White's chapter deals with the effect of foveal load on skipping words. Prior research (Henderson & Ferreira, 1990; Kennison & Clifton, 1995; Schroyens, Vitu, Brysbaert, & d'Ydewalle, 1998; White, Rayner, & Liversedge, 2005) has demonstrated that preview benefit is reduced with greater foveal load. In her chapter, White shows that foveal load does not influence word skipping. The other two chapters in this section largely provide further evidence for the conclusion that difficulty of processing or accessing the meaning of a word strongly influences how long readers look at it. Morris deals with eye movements and lexical ambiguity, while Juhasz deals with the effect of transparency of compound words on eye movements.

In the remainder of this section, we will briefly review findings which have demonstrated effects due to (1) word frequency, (2) word familiarity, (3) age-of-acquisition, (4) number of meanings, (5) morphology, (6) contextual constraint, and (7) plausibility. Our interest in this section is in how a word is identified as distinct from how it is integrated into the sentence that carries it. However, we recognize that this distinction between recognition and integration needs a great deal of theoretical refinement. It may prove best to recognize that in addition to factors inherent to an individual word, factors involving the word's relation to other words may affect how it is read. It may prove best to draw theoretical distinctions at points other than recognition vs. integration (c.f., the E-Z Reader's distinction between two stages of accessing a word; Reichle et al. 1998). At some points, we hedge our bets on whether the effect of some factor, e.g., plausibility, is best discussed in connection with word recognition or sentence integration, and discuss the data about the effect of the factor in both sections of this chapter.

We will focus on the measures most commonly used to investigate the process of identifying a word: first fixation duration (the duration of the first fixation on a word, provided that the word wasn't skipped), single fixation duration (the duration on a word when only one fixation is made on the word), and gaze duration (the sum of all fixations on a word prior to moving to another word). In the following section, we will concentrate on how integrating an identified word into syntactic and semantic structures affects eye movements. Since some of the factors to be discussed in the first section may affect both word identification and integration, we will revisit their effects in the second section.

Word Frequency. How long readers look at a word is clearly influenced by how frequent the word is in the language (as determined from corpus data). Rayner (1977) first annecdotally noticed that readers look longer at infrequent words than frequent words and Just and Carpenter (1980) reported a similar frequency effect via a regression analysis. However, frequency and word length are invariably confounded in natural language. Rayner and Duffy (1986) and Inhoff and Rayner (1986) therefore controlled for word length and demonstrated that there was still a strong effect of frequency on fixation times on a word. These researchers reported first fixation and gaze duration measures. The size of the frequency effect in Rayner and Duffy was 37 ms in first fixation duration and 87 ms in gaze duration; in Inhoff and Rayner it was 18 ms in first fixation duration and 34 ms in gaze duration (when the target word processing had not been restricted in any way). Since these initial reports, numerous studies have demonstrated frequency effects on the different fixation measures (see Rayner, 1998; Reichle et al., 2003 for summaries). One interesting finding is that the frequency effect is attenuated as words are repeated in a short passage (Rayner, Raney, & Pollatsek (1995) so that by the third encounter of a high or low frequency word, there is no difference between the two. The durations of fixations on low frequency words decreases with repetition; the durations of fixations on high frequency words also decreases, but not as dramatically as for low frequency words.

Word familiarity. Although two words may have the same frequency value, they may differ in familiarity (particularly for words that are infrequent). Whereas word frequency is usually determined via corpus counts, word familiarity is determined from rating norms in which participants have to rate how familiar they are with a given word. Effects of word familiarity on fixation time (even when frequency and age-of-acquisition are statistically controlled) have been demonstrated in a number of recent studies (Chafin, Morris, & Seely, 2001; Juhasz & Rayner, 2003; Williams & Morris, 2004).

Age-of-acquisition. Words differ not only in frequency and familiarity, but also in how early in life they were acquired, and this variable influences how long it takes to process a word

(Juhasz, 2005). Age-of-acquisition is determined both by corpus counts and by subjective ratings. Juhasz and Rayner (2003, 2006) demonstrated that there was an effect of age-of-acquisition above and beyond that of frequency on fixation times in reading. Indeed, in the Juhasz and Rayner studies, the effect of age-of-acquisition tended to be stronger than that of word frequency.

Number of meanings. A very interesting result is that there are clear effects of lexical ambiguity on fixation times. Rayner and Duffy (1986), Duffy, Morris, and Rayner (1988), and Rayner and Frazier (1989) first demonstrated these effects, which have subsequently been replicated a number of times (most recently by Sereno, O'Donnell, & Rayner, 2006 and by Morris in her chapter in this section). The basic finding is that when a balanced ambiguous word (a word with two equally likely but unrelated meanings) is encountered in a neutral context, readers look longer at it than an unambiguous control word matched on length and frequency, whereas they don't look any longer at a biased ambiguous word (a word with one dominant meaning) in a neutral context than an unambiguous control word. In the latter case, apparently the subordinate meaning isn't registered; however, if the later encountered disambiguating information makes clear that the subordinate meaning should be instantiated, then there is considerable disruption to reading (long fixations and regressions). When the disambiguating information precedes the ambiguous word, readers don't look any longer at the balanced ambiguous word than the control word. Apparently, the context provides sufficient information for the reader to choose the contextually appropriate meaning. However, in the case of biased ambiguous words when the subordinate meaning is instantiated by the context, readers look longer at the ambiguous word than the control word. This latter effect has been termed the subordinate bias effect. Rayner, Cook, Juhasz, and Frazier (2006) recently demonstrated that a biasing adjective preceding the target noun is sufficient to produce the effect.

A interesting study by Folk and Morris (2003) suggests, however, that effects of lexical ambiguity interact with syntactic context. Folk and Morris found that the subordinate bias effect disappears when a biased ambiguous word has one noun meaning and one verb meaning (e.g., *duck*) and only the subordinate meaning provides a syntactically legal continuation of the sentence. In a second experiment, Folk and Morris preceded balanced ambiguous words with a context that allowed a noun continuation, but not a verb continuation. They found increased reading times on target words with two noun meanings, but not on target words that were ambiguous between noun and verb meanings. A possible moral of the two experiments, taken together, is that assignment of a word's syntactic category precedes access to meaning. As a result, when a word's two meanings are associated with different syntactic categories and only one of these categories can legally continue the sentence, competition between the two meanings does not occur. It is an open question how the results obtained by Folk and Morris should be reconciled with cross-modal priming results obtained by Tanenhaus and colleagues (Seidenberg, Tanenhaus, Leiman, & Bienkowski, 1982; Tanenhaus & Donenwerth-Nolan, 1984; Tanenhaus, Leiman & Seidenberg, 1979), who reach the conclusion that syntactic context does not prevent access to inappropriate meanings. It is worth noting that the eyetracking paradigm, due to its naturalness, may be less likely to introduce strategic effects or task demands.

The nature of the mechanisms underlying these effects is still under debate. However, the experiments described here demonstrate that in general, the number of meanings a word has influences how long readers will look at it. Likewise, words that are phonologically ambiguous (like *tear* and *wind*) also yield differential looking times (Carpenter & Daneman, 1981), and words with two different spellings but the same pronunciation (and two different meanings, such as *beech-beach, soul-sole,* and *shoot-chute*) also produce differing fixation times (Folk, 1999; Jared, Levy, & Rayner, 1999; Rayner, Pollatsek, & Binder, 1998).

Finally, it is interesting to note that Frazier and Rayner (1987) reported that words with syntactic category ambiguity (*desert trains* can be a noun-noun compound or a noun and a verb) resulted in delayed effects in contrast to lexical ambiguity which results in immediate effects. Pickering and Frisson (2001) likewise reported delayed effects with verbs that are ambiguous in meaning. Also, Frazier and Rayner (1990) found that in contrast to nouns with two meanings (which are typically used in lexical ambiguity studies) reading time is not slowed for words with two senses (such as the two senses of *newspaper*).

Morphological effects. Traditionally, most recent research on word recognition has dealt with rather simple mono-morphemic words. This tradition has also been largely true of research on eye movements and word recognition. More recently, however, a fair number of studies have examined processing of morphemically complex words. This newer tradition (Hyönä & Pollatsek, 1998; Pollatsek, Hyönä, & Bertram, 2000) started with the processing of Finnish words (which by their very nature tend to be long and morphologically complex). Hyönä and Pollatsek (1998) found that the frequency of the first morpheme (and to a lesser extent, the second morpheme) in two-morpheme words influenced how long readers fixated on the word, even when the overall word frequency was controlled, implying that recognition of the word decomposing it into its component morphemes. Morphological decomposition of compound words has recently been demonstrated with English words (Andrews, Miller, & Rayner, 2004;

Juhasz, Starr, Inhoff, & Placke, 2003). Pollatsek and Hyönä (2003) recently demonstrated that transparency had no effect on fixation times on morphologically complex words. In her chapter in the present volume, Juhasz did find a main effect of transparency in gaze durations. However, both semantically transparent and opaque compound words also exhibited morphological decomposition supporting Pollatsek and Hyönä's main conclusion that both types of compounds are decomposed during word recognition.

Contextual constraint. Like word familiarity, word predictability is determined via norming studies (after experimenters have prepared sentence contexts such that certain target words are either predictable or unpredictable from the context). Cloze scores are then used to confirm the experimenter's intuitions as to how constrained a word is by the context. Considerable research has demonstrated that words that are predictable from the preceding context are looked at for less time than words that are not predictable. This result was first demonstrated by Ehrlich and Rayner (1981) and confirmed a number of times, most notably by Balota, Pollatsek, and Rayner (1985) and Rayner and Well (1996), and most recently by Rayner, Ashby et al. (2004) and by Ashby, Rayner, and Clifton (2005). Not only are fixation time measures shorter on high predictable words than low predictable words, readers also skip over high predictable words more frequently than low predictable words (Ehrlich & Rayner, 1981; Rayner & Well, 1996).

Plausibility effects. Although plausibility clearly affects sentence interpretation and integration, we discuss it here because it may also affect word recognition. Several studies have examined whether manipulations of plausibility or anomaly have effects on eye movements that are immediate enough to suggest that the manipulations may affect word recognition (Murray &

Rowan, 1998; Ni, Crain, & Shankweiler, 1996; Ni, Fodor, Crain, & Shankweiler, 1998; Rayner, Warren, Juhasz, & Liversedge, 2004). We discuss Rayner et al. in some detail in the second section of this chapter. Briefly, they showed that an outright anomaly (e.g., *John used a pump to inflate the large carrots....*) affected time to read the critical word (*carrots*). However, the effect did not appear on the first fixation measure, which is ordinarily sensitive to word recognition difficulty, but only on gaze duration. A simple implausibility (*...used an axe to chop the large carrots...*) only affected the go-past measure (described in the next section of this chapter as an arguably-late measure) and gaze duration on the word following the critical word, suggesting that its effects are limited to processes of integrating the implausible word into the sentence context.

Interim summary. Up to this point, we have reviewed some basic findings of how certain variables arguably related to word recognition mechanisms manifest themselves in the eye movement record. In general, the primary assumption is that lexical factors play a large role in influencing when the eyes move, and these effects appear in first fixation and first pass measures. And, as we noted earlier, the most successful models of eye movement control are based on the premise that how long readers look at a word is influenced by the ease or difficulty associated with accessing the meaning of the word. Factors that presumably affect word recognition are currently utilized in the models, including our favored E-Z Reader model (Reichle et al., 1998) to predict fixation times. These factors include word frequency, morphological complexity (Pollatsek, Reichle, & Rayner, 2003), and number of meanings (Reichle, Pollatsek, & Rayner, this volume). We ended this section by suggesting that two higher order "relational" factors (contextual constraint and plausibility) may affect word recognition under some conditions, e.g., when their operation can be triggered before the target word is fixated (as in a predictable word) or when their manipulation is strong enough (as in anomaly). We turn now to the more difficult issues of the effect of high-order factors on eye movements.

Effects of syntactic, semantic, and pragmatic factors

While single-fixation, first-fixation, and gaze duration are the measures of choice for studying the time course of word identification, a wider variety of measures is commonly used in measuring how factors that guide integration of text affect eye movements. For the most part, authors of the experiments that we will discuss in this section identify critical regions of text, sometimes consisting of as many as three or four words (occasionally even more), and then examine how long it takes readers to read the regions of interest. The standard measures are: first pass reading time (the sum of all fixations in a region from first entering the region until leaving the region, given that the region was fixated at least once), go-past or regression path duration (the sum of all fixations in a region from first entering the region until moving to the right of the region; fixations made during any regressions to earlier parts of the sentence before moving past the right boundary of the region are thus included in this measure, again given that the region was fixated), regressions-out (the probability of regressing out a region, generally limited to the first-pass reading of that region), second pass reading time (the sum of all fixations in a region following the initial first pass time, including zero times when a region is not refixated), and total reading time (the sum of all fixations in a region, both forward and regressive movements, again given that the region was fixated). First fixation durations are also sometimes reported, especially when the disambiguating region is short or when the researcher is interested in spillover effects from the previous region, but when regions are long and the disambiguating material is not likely to be included in the initial fixation, the first fixation measure is inappropriate. Measures such as first pass time (and first fixation time) are often referred to as "early" measures; second pass time (and total time, to the extent that it reflects second pass time rather than first pass time) are referred to as "late" measures (Rayner, Sereno, Morris, Schmauder, & Clifton, 1989). The go-past and regressions-out measures are sometimes considered "early," sometimes "late," measures. The occurrence of a regression reflects some difficulty in integrating a word when it is fixated, arguably an early effect.. The go-past measure reflects this effect, but also reflects the cost of overcoming this difficulty, which may well occur late in processing. The terms "early" and "late" may be misleading, if they are taken to line up directly with first-stage vs second-stage processes that are assumed in some models of sentence comprehension (Rayner, Carlson, & Frazier, 1983; Frazier, 1987). Nonetheless, careful examination of when effects appear may be able to shed some light on the underlying processes. Effects that appear only in the "late" measures are in fact unlikely to directly reflect first-stage processes; effects that appear in the "early" measures may reflect processes that occur in the initial stages of sentence processing, at least if the measures have enough temporal resolving power to discriminate among distinct, fast-acting, processes.

As argued in the first section of this chapter, a clear, if incomplete, picture seems to be developing about how lexical factors control eye movements. The same is not true about high-level factors. The earliest eye-movement research on such factors (Frazier & Rayner, 1982) held promise that syntactic factors would have sharp and understandable influences on eye movements. Frazier and Rayner examined the reading of sentences like (1) and (2), and found that the very first fixations on the disambiguating region (presented in bold face in the examples) were slowed, compared to earlier fixations, when they resolved a temporary ambiguity in favor of the theoretically-unpreferred reading (in 4, when *this* was absent). This disruption persisted through the next several fixations, and also appeared as an increased frequency of regressions. Eye movements appeared to provide a clear window onto syntactic "garden-pathing" (Bever, 1970).

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

2. (The lawyers think his/His) second wife will claim the entire family inheritance (./**belongs to** her.)

This early research was open to some criticisms. The disruption in (1) appeared in a region that followed the absence of an arguably-obligatory comma (or prosodic break); the disruption in (2) appeared in a sentence-continuation that had no counterpart in the non-disruptive control condition. But the force of the missing-comma criticism is compromised by the fact that an equally-obligatory comma is missing in the control condition, with no effect on reading times, and the lack of a closely-matched control in (2) has been corrected in later research (Rayner & Frazier, 1987).

On balance, it appeared that syntactic processing difficulty could be identified by quickly-appearing disruptions in the eyetracking record. Rayner et al. (1983) provided evidence for a similar conclusion when an initial syntactic misanalysis is signaled by a semantic anomaly. They found increased first-pass reading times for sentences like (3b), where the first noun is semantically anomalous under the presumably-preferred initial analysis, compared to sentences like (3a). The effect appeared in the initial fixations in the disambiguating region, where it was significant when averaged over the first three fixations, and apparent on the first fixation (and significantly longer than the previous fixation)

3. a. The kid hit the girl with a **whip before he got off the subway.**

b. The kid hit the girl with a **wart before he got off the subway.**

Later research, unfortunately, has not always demonstrated such clear, immediate, and regular effects of syntactic and semantic factors on eye movements. We will briefly describe one example of how a manipulation of syntactic and semantic factors can have apparently very different results, depending on what eye movement measures one looks at (this analysis was presented by Clifton, 2003).

An early demonstration of syntactic effects on eye movements was presented by Ferreira and Clifton (1986), who showed disruption in the disambiguating region of sentences like (4) when they were temporarily ambiguous (when the *who/that was* phrase was absent) compared to when they were not ambiguous (when the *who/that was* phrase was present). The effect appeared both when the initial noun was animate (4a) and when it was inanimate (4b) and implausible as the subject of the following verb.

4. a. The defendant (who was) examined **by the lawyer** proved to be unreliable.

b. The evidence (that was) examined **by the lawyer** proved to be unreliable.

The disruption appeared in first pass reading time measures, and was taken to show that the semantic implausibility of the presumably-preferred main clause analysis in (4b) did not override initial syntactic parsing preferences. This conclusion was challenged by Trueswell, Tanenhaus and Garnsey (1994), who argued that some of the Ferreira and Clifton items that were claimed to semantically block the preferred main clause reading did not do so. Trueswell et al. prepared two more adequate sets of materials, carefully normed, and showed that any effect of ambiguity on first pass reading time was nonsignificant (nearly zero, in one experiment) in materials like (4b), where semantic preferences weighed against the main clause analysis. They concluded that their experiment did demonstrate that semantic factors could overturn syntactic preferences, favoring an interactive, constraint-satisfaction, model over the modular serial model favored by Ferreira and Clifton.

Clifton, Traxler, Mohamed, Williams, Morris, and Rayner (2003) revisited the question, using materials taken from Trueswell et al. (1994). In two experiments they varied parafoveal preview of the disambiguating information and examined the effects of participants' reading span. Abstracting from these factors (which for the most part did not affect the magnitude of the disruption triggered by a temporary ambiguity), the first pass time measures were similar to those reported by Trueswell et al. (1994). Semantic biases reduced the first pass reading time measure of the temporary ambiguity effect to nonsignificance in sentences like (4b) (although, similar to Trueswell et al., the interaction of semantic bias and temporary ambiguity was not fully significant, and, unlike Trueswell et al. the ambiguity effect did not go fully to zero). However, a very different pattern of results was observed for the go-past (or regression path duration) and proportion of first-pass regressions out measures (Figure 1). These measures showed disruptive effects of temporary ambiguity that were as large in semantically-biased inanimate-subject sentences like (4b) as in animate-subject sentences like (4a) where no semantic bias worked against the presumed preference for a main clause analysis.

Insert Figure 1 about here

Clifton et al. (2003) concluded that a full examination of the eye movement record indicated that initial syntactic parsing preferences were not overcome by semantic biases, although such biases clearly affected overall comprehension difficulty for both temporarily ambiguous and unambiguous sentences. However, this conclusion does leave several salient questions unanswered. The first is, why did Ferreira and Clifton (1986) find first pass time garden-path effects for both animate and inanimate subject sentences while later research found nonsignificant first pass time effects for inanimate subject sentences? Perhaps their sentences were inadequately controlled, as suggested by Trueswell et al. (1994). Examination of the effects for individual items in the Ferreira and Clifton data, however, does not support this claim: First pass effects were observed both for items that Trueswell et al. later found to be acceptable and for inadequately-biased items. A more likely cause is that Ferreira and Clifton used a display that presented only 40 characters on a row, frequently necessitating a line break before the beginning of the disambiguating by-phrase region. This would have prevented parafoveal preview of the by-phrase (although we note that absence of parafoveal preview in the boundary-change conditions of Clifton et al., 2003, did not affect the size of the ambiguity effect), it could have encouraged a commitment to the apparent subject-verb structure of the material on the first line, and it could have discouraged regressions from the disambiguating region (which would have had to cross lines of text, unlike Clifton et al., 2003).

A second question is, why in the Clifton et al. (2003) data did significant garden-path effects appear in first pass times for sentences with animate subjects but only in regressions and go-past times for sentences with inanimate subjects? Answering this question requires a better understanding of the relation between comprehension difficulty and eye movements than we now have. A detailed examination of the Clifton et al. (2003) data (reported by Clifton, 2003) did not answer the question. Perhaps the most salient result of this examination is that while regression frequency increased in the syntactically ambiguous conditions, regressions from the disambiguating region were quite infrequent and the increase in regression frequency was quite small (from approximately 10% to 13% for the animate subject condition, and from approximately 5 to 8% for the inanimate subject condition, pooling data from Experiments 1 and 2; see Figure 1). The increase in the size of the garden-path effect in the inanimate subject condition from first-pass to go-past times thus has to be attributed to eye movement events that take place on a very small minority of the trials. It is even possible e that first pass fixation durations may have been increased by temporary ambiguity, even in the animate subject condition, on only a small minority of trials. This would contrast sharply with what is true of effects of lexical frequency on fixation duration, where the entire time distribution appears to be shifted upwards for low frequency words (Rayner, 1995; Rayner, Liversedge, White, and Vergilino-Perez, 2003). To our knowledge, no existing research on syntactic garden-paths provides data on a large enough number of sentences to permit a convincing distributional analysis to be made. It remains a challenge to researchers to devise a way of asking the question of whether first pass reading times typically or exceptionally increase upon the resolution of a garden path.

Even if it is not currently possible to provide a general answer to the question of whether syntactic (and other high-level factors) affect eye movements on many or on few trials, it may be possible to make some progress toward understanding how high-level factors affect eye movements by examining the existing literature (see Boland, 2004, for related discussion). As suggested above, some of the early research indicated that syntactic or semantic anomaly slowed eye movements essentially immediately. Other, more recent, research suggests that under some conditions, such anomalies may trigger regressive eye movements rather than affecting fixation durations. Still other research suggests that effects of anomaly may in some instances appear only later in the eye movement record. Given the frequently-stated desire to use eye movements to make inferences about the immediacy of various levels of processing in language comprehension (Rayner, Sereno, Morris, Schmauder, & Clifton, 1989; Rayner & Sereno, 1994), we believe it may be useful to take stock of just when and how a wide variety of high-level factors impact the eye movement record.

Survey of eyetracking articles. We identified 100 articles that used eye movements to explore the effects of syntactic, semantic, and pragmatic factors on sentence comprehension (listed in Table 1). We attempted to include all such articles that had been published in peer-reviewed journals at the time of writing.[1] We did not include articles where the main factor of interest involved discourse structure, text properties, inferences, or anaphora (although we did include articles where the effects of discourse structure, etc., on the effect of some syntactic or semantic property of a sentence were studied). We generally did not include papers published as chapters in edited books, but we did include a very few that struck us as making a unique contribution. We did not include any unpublished papers, apart from a few of our own. The 100 articles under consideration are those indicated by a number in Table 1. Our following discussion refers to these articles by this number.

INSERT TABLE 1 ABOUT HERE

We examined each of these articles, categorizing the experiments they contained in several ways. The results of this categorization appear in Tables 2 and 3. The final "ALL"

[1] If we have missed any, we apologize to the authors, and ask them to accept our oversight as an error, not as a snub.

column of these tables lists the numbers (see References) of all the articles that fall in a given category. These tables indicate a variety of properties of the experiments, including a specification of the first region in which an effect of the primary manipulated factor appears in each reported eyetracking measure. The measures are FF (first fixation), FP (first pass), GP (go-past), SP/TT (either second pass or total time, whichever was reported), and RO (regressions out).

If an experiment involved the resolution of a temporary syntactic ambiguity, it is listed in Table 2. In this table, Region D indicates the region in which the disambiguation first appeared (and D+1 the next region). SP/TT effects are reported if they occurred in any region. If an experiment did not involve temporary ambiguity, but instead involved factors hypothesized to affect predictability, plausibility, complexity, or similar properties of sentences, it appears in Table 3. In this table, Region C indicates the critical region, the region involving the predictable/plausible/etc. word or words. In both tables, brief descriptions of the temporary ambiguity or the primary manipulated factor appear in the first column. In Table 2, the second column indicates the nature of the disambiguating material. "Category" means that disambiguating information was conveyed by the syntactic category of the disambiguating phrase (e.g., in the SCO/MCS ambiguity, an ambiguity between subordinate clause object and main clause subject – see Notes to Table 2 – "category" means that the disambiguation was conveyed by the fact that the main verb of the sentence followed the NP that was temporarily ambiguous between an object and a subject). The number of an article in Table 1 appears in the earliest column of each measure for which a statistically significant effect was reported. Note that experiments differ substantially in the length of the critical or disambiguating region, and that experiments where this region is very short may tend to yield effects that emerge only on the following region. Note further that few experiments included reports of all measures, so the absence of an article-number in a column does not mean that there was a null effect; it may simply mean that the effect was not reported for the measure in question.

Some multi-experiment articles appear in multiple categories of a table, or in both tables. In a great many cases, we have abstracted away from the factors of most interest to the authors of an experiment. For instance, the authors may have been interested in the effect of plausibility or context on how a syntactic garden-path is resolved. In our tables, since we are interested primarily in what aspects the eyetracking record reflect what types of processing difficulty, we simply categorize the experiment on the basis of the type of garden-path and how it was eventually resolved, and report the earliest appearances of the resolution in any condition of the experiment.

Insert Table 2 about here

Tables 2 and 3 are presented largely to stimulate a deeper examination of how eye movements reflect sentence processing. These tables, by themselves, cannot present all relevant information about an experiment. For instance, authors of different experiments on the same topic commonly differ in how they divide their sentences into regions, which clearly can affect where an eyetracking effect can appear. However, even a superficial examination of these tables supports some generalizations. Consider first Table 2, the "garden-path" table. It is clear that few first fixation effects appear. This is largely because few authors report such effects. This is justified, when the disambiguating region contains multiple words, and the first word of the region does not contain disambiguating material. No first fixation effect should be expected if the first fixation does not land on critical material. However, in cases where the first (or only) word of a disambiguating region was of a syntactic category that reversed a strong initial preference for one interpretation (e.g., the SCO/MCS, or the MC/RC, main clause/relative clause, ambiguity), first fixation effects have been reported. The only instance of a first fixation effect on the following region appears in reference 80, where it is probably a spillover effect. First pass effects are very common, certainly where disambiguation is carried by syntactic category, but also, in some cases (e.g., ambiguous attachment of a prepositional phrase, PP, to a verb or a noun, as in (6), cited earlier), sheer implausibility of the initially-preferred interpretation can result in first pass effects. One can conclude that semantic interpretation (at least, of the initially-preferred alternative) is done very quickly indeed, and can appear quickly in the eyetracking record. Note, however, as discussed above, currently available data does not allow us to decide whether such an effect occurs on most or all trials, or only on a possibly-small subset of trials.

There are rather few cases where an effect shows up in go-past but not in first pass (as was the case for the inanimate-subject items in Clifton et al., 2003), but there are some. The greatest number of these are in the object/subject "late closure" (SCO/MCS) ambiguity, but some appear in PP attachment, long distance dependencies (filler-gap constructions), and subject vs object extracted relative clauses. The appearance of effects in percentage of regressions out (RO) of the disambiguating region that did not appear in first pass time probably reflects a similar dynamic. These can be seen in some of the cases just discussed. A very late effect sometimes appears as regressions out of the region following the disambiguating region (e.g., in some cases of PP, adverb, or relative clause attachment). Second pass/total time effects in the absence of effects already discussed (first pass, go-past, regressions out) are almost non-existent, appearing only in articles 1, 44, 54, and 61. We note that the generally-low power of experiments on sentence processing leaves open the possibility that these experiments simply failed to detect a real effect in the earlier measures. We further note that late effects in the absence of early effects are reported for some conditions of the experiments reviewed, e.g., the unambiguous inanimate-subject conditions of Clifton et al. (2003) (15). In these cases, they may reflect some general comprehension difficulty, not associated with the resolution of a syntactic ambiguity.

One final point is worth bringing up, even though it is not reflected in Table 2. We examined all the relevant articles for evidence about whether reading is slowed in the ambiguous region, compared to an unambiguous control condition. Models of sentence processing that posit a time-consuming process of competition among alternative analyses apparently predict such slowing. These models include MacDonald, Pearlmutter, and Seidenberg (1994), and McRae, Spivey-Knowlton, and Tanenhaus (1998), and Spivey and Tanenhaus (1998); see Gibson and Pearlmutter, 2000; Lewis, 2000; and Traxler, Pickering, and Clifton, 1998, for some discussion.

It turns out that there are very few instances of such a slowing in the ambiguous region. In most cases, if the data are presented, no slowing appears, and in fact, there are several reports of a speedup in an ambiguous region as compared to an unambiguous region (see References 28, 90, 96, and 98). There are a very few specious cases of apparent slowing (e.g., References 13, 19, 36, 47, 60), but they all appear to be due to semantic implausibility of the preferred interpretation rather than a slowdown due to ambiguity per se. However, there are a few cases of apparent slowing due to ambiguity. Most of these involve the main clause/reduced relative ambiguity, and include References 15, 56, and 58. The apparent slowing in an ambiguous phrase also appears in References 43 and 74, which examined the direct object/sentence complement ambiguity.

Several of these (15, 43, 58, 74) could be dismissed as simply reflecting fast reading after the highly frequent series of words in the disambiguating condition *that was* and the slowdown in Reference 43 could actually reflect the semantic implausibility of attaching a prepositional phrase as a modifier of the preceding verb, a normally-preferred analysis. However, Reference 56 (Ni et al., 1996) cannot be dismissed so easily since disambiguation in that case was carried by the morphology of the otherwise-ambiguous verb (e.g. *The horse raced* vs. *ridden...*), but note that different sentences with different lexical items and different content were used in the ambiguous and unambiguous conditions, making direct comparison uncertain. None of the remaining studies of the main clause/reduced relative clause ambiguity reported slower reading in the ambiguous region. It is possible that the experiments that did not detect slowing in the ambiguous region simply did not have enough power to detect the effect, but it is also possible that some of the participants in the experiments that did report the effect became aware of the occasional ambiguity and deliberately read it cautiously.

Table 3 encompasses articles examining effects on eye movements generated by a range of factors other than syntactic ambiguity. Many of these articles examine effects on word processing, but we discuss them here, as well (in some cases) as in the first section of this chapter, because these articles focus on the syntactic, semantic, or pragmatic relationship between a word and its context.

Insert Table 3 about here

Relatively few eyetracking studies have examined the effect on eye movements of encountering a syntactically or semantically anomalous word in printed text. It is somewhat surprising that of the four studies (9, 17, 57, 59) that have explicitly examined responses to syntactic anomaly (e.g., agreement errors), only two (9, 17) found effects appearing on the anomalous word. On the other hand, four of the five studies of semantic or pragmatic anomaly (9, 55, 71, 85) have found increased first fixation duration or gaze duration on the offending word (57 reported only a late effect). Of course, it is possible that which measure an effect first appears in reflects the magnitude of the processing disruption occasioned by the effect, and not simply the timing of the processes that the effect reflects.

It is interesting to contrast the paucity of eyetracking studies of anomaly with the profusion of event-related potentials (ERP) studies that have focused on brain responses to anomalous words. The earliest reported electrophysiological response to a syntactic word category violation (the early left anterior negativity, or ELAN; Hahne & Friederici, 1999; Neville, Nicol, Barss, Forster, & Garrett, 1991) occurs 150-200 ms after the onset of the critical word, while the typical response to a semantic violation (the N400, first identified by Kutas & Hillyard, 1980) peaks about 400 ms after word onset. However, whether agreement violations trigger an early effect is not certain, with some studies reporting such an effect (Coulson, King, & Kutas, 1998; Deutsch & Bentin, 2001; Osterhout & Mobley, 1995) and others reporting only a much later effect, the P600 (Hagoort, Brown, & Groothusen, 1993; Munte, Heinze, & Mangun, 1993; Osterhout, McKinnon, Bersick, & Corey, 1996). In sum, the overall picture from both ERP and eye movement research suggests that the question of exactly when syntactic and semantic anomalies each affect language comprehension is still to be settled.

A study by Rayner et al. (2004; 71) that was mentioned in the earlier discussion of plausibility effects on word recognition suggests that semantic anomaly is probably not a unitary phenomenon with respect to its effect on eye movements. Rayner et al. had participants read sentences such as:

5. John used a knife to chop the large carrots for dinner last night.

6. John used an axe to chop the large carrots for dinner last night.

7. John used a pump to inflate the large carrots for dinner last night.

In all sentences, the target word is *carrots*. Sentence (5) is a normal control condition; in (6), the target word is an implausible theme given the combination of verb and instrument; and in(7), the target word is an anomalous theme of the verb. Rayner et al. found that while (6) only caused mild disruption to reading, appearing in the go-past measure on the target word and in gaze duration on the following word, (7) caused a more rapid disruption, appearing as an increase in gaze duration on the target word. Given that this relatively subtle difference in the type of implausibility produces a clear difference in the eye movement record, it is not surprising that when semantic anomaly or implausibility has been used as a means of disambiguation in studies of syntactic ambiguity processing, the time course of its effect has varied considerably.

Even within the range of words that are not semantically anomalous given the preceding context, there are, as was discussed above, early effects on eye movements of the word's semantic fit. Five studies (5, 18, 35, 53, 72) have examined the effect of a word's predictability or "contextual constraint"; in general, this is defined in terms of the word's cloze probability (i.e., the probability that informants will produce the target word as the likely next word in the sentence, given the sentence up to that word). The basic finding is that when a word is highly predictable, the first fixation duration or gaze duration on the word is decreased. One article (53) has reported that the transitional probability between two words in corpora has an independent facilitatory effect on processing of the second word, though a second article (72) has reported results suggesting that when overall predictability is well-controlled, transitional probability does not have an independent effect.

In a recent study (78) that is related to the issue of predictability, we demonstrated that when a word's syntactic category is predictable, though the word itself is not, gaze duration is reduced on either the word itself or on the next word, depending on the syntactic construction. For example, after a determiner (e.g., *the*), gaze duration is shorter on a noun (which must occur in the phrase beginning with the determiner) than on an adjective (which is legal but optional), even when factors such as length, frequency, and lexical predictability held constant. Another study that specifically examined syntactic category effects (75) found that readers tend to refixate function words more frequently than content words, though somewhat surprisingly this study did not find any significant earlier effects of this distinction between word classes.

In Table 3 we have identified four studies (33, 34, 86, 91) that manipulated the nature of the semantic processing that is required on a word, under the heading of *lexical semantics*. Since these studies focused on a range of types of semantic processing, it is not surprising that there is considerable variation in the time course with which the manipulations affected eye movements. At one extreme, Frisson and Frazier (2005; 33) found that when a mass noun appears in the plural (e.g., *some beers*), or a count noun appears in the singular with a plural determiner (e.g., *some banana*), the first fixation duration on the critical word is lengthened. On the other hand, in a study by Traxler, Pickering, and McElree (2002; 91; see also Pickering, McElree, & Traxler, 2005) that examined so-called coercion, where a noun with no intrinsic temporal component must be interpreted as an event (as in the phrase *finish the book*), the earliest significant effects were on the word after the critical word.

We identified four articles (40, 70, 80, 95) that investigated the effect of syntactic complexity of a phrase in the absence of syntactic ambiguity. All of these reported an effect of increased complexity on first fixation duration or first pass time in the critical region. To cite just one example (80), we have recently conducted a study of the processing of so-called Heavy NP Shift (Ross, 1967), in which a verb's direct object appears at the end of the sentence rather than adjacent to the verb. The experiments varied the point in the sentence at which the reader had to construct this complex syntactic analysis. At the point at which the Heavy NP Shift analysis had to be constructed, readers consistently slowed down, made regressive eye movements, or both.

Finally, we also included a number of articles examining semantic processing effects on linguistic structures larger than a single word (7, 23, 25, 27, 52, 73, 84, 99). Again, a rather diverse collection of phenomena are investigated in these articles. Several of the studies report early effects of their manipulations, but two report only second pass or total time effects. We suspect, in addition, that this may be one area in which researchers have obtained various null effects that have remained unpublished.

Conclusions

Measuring eye movements during reading has greatly enhanced understanding of how people identify words and comprehend sentences. The early impact of linguistic variables such as lexical frequency and age-of-acquisition on eye movements has shown that eye movements quite directly reflect linguistic processing. In turn, the speed of eye movements, and their tight linkage to at least some parts of the reading process, has provided convincing support for the thesis that language processing is often essentially immediate, at least in the sense that a word is typically interpreted and integrated into the communicated message while the eyes are still fixated on it (see Marslen-Wilson, 1973, for an early statement of this thesis in the domain of listening). Eye movements have allowed researches to probe the early stages of reading in a clear and direct fashion that is exceeded by no other technique we know of.

In the domain of word identification, eye movement data have been extremely clear and orderly. Intrinsic lexical factors generally have their effect on very early measures of eye movements, including first fixation and gaze duration, and some relational factors that may affect word identification do as well. The basic phenomena seem to be sufficiently consistent and replicable to support the development of theories in a "bottom-up" fashion. To be sure, there is still plenty of room for theorists to argue about the best way to interpret data (see the discussion following Reichle et al., 2003). But the strategy of first identifying solid empirical phenomena and then building formal theories that account for them has paid off very well in this domain.

The domain of sentence comprehension is similar in some ways, but very different in others. Eye tracking measures have shown that much, if not quite all, of sentence comprehension is nearly immediate. Reflections of syntactic or semantic anomaly or complexity sometimes can appear very quickly in the eye movement record, as do effects of recovering from garden-paths. Eyetracking measures have also shown that syntactic knowledge and at least some kinds of semantic, pragmatic, and real-world knowledge have effects even during fixations on the phrase that provides access to this knowledge. But our survey of the literature shows that the effects of sentence comprehension factors are more variable than the effects that word identification factors, such as lexical frequency and lexical ambiguity, have on eyetracking measures.

Some of this variability may reflect experimental limitations more than deep-seated differences between lexical processing and sentence integration. For instance, the greater variability in length of critical regions in studies of sentence integration than in the length of words that constitute critical regions in studies of lexical processing certainly gives rise to more variability in where an effect will appear in the eyetracking record. Further, we suspect sentence integration and comprehension processes are more sensitive than word recognition processes to the task and goals given to the reader, leading to greater variability across studies.

On the other hand, the variability in effects of sentence comprehension factors may be more fundamental. A reader has more options about how to deal with processing difficulty when the difficulty is occasioned by plausibility or complexity or syntactic misanalysis than when it is occasioned by difficulty recognizing a word. In the latter case, about the only option the reader has is to continue looking at the word (or giving up, or guessing). In the former case, the reader may go back into earlier text to try to identify problems, or continue thinking about the phrase that made the difficulty apparent, or plunge ahead, hoping that later information will resolve the issue. Furthermore, in contrast to normal word recognition, a wide range of factors contribute to sentence comprehension. We are far from understanding how these factors are coordinated (a topic of raging disagreement which we have largely avoided in our review) and whether their coordination is modulated by differences in a reader's abilities and strategies. Suffice it to say that the greater flexibility in dealing with sentence comprehension difficulty and the wide range of factors that affect it could mean that high-level processing shows up in the eye movement record in a variety of different ways, with any one effect appearing only occasionally.

In our view, the "high-level" variables that affect sentence interpretation are much more complex, both in their definition and in their effect, than the variables that govern much of the variation in word identification. We suspect that understanding how these high-level variables operate is not something that can be induced from observations of eyetracking phenomena (as we claim has been true in large part in the domain of word identification). Rather, we suspect that understanding must be guided by the development of more explicit theories than now exist of how syntactic, semantic, pragmatic, and real-world knowledge guide language comprehension. We hold hope that development of such theories will help make sense of the empirical variability that we have illustrated in Tables 1 and 2.

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Table 2: Classification of Articles Examining Effects of Temporary Ambiguity

Structure	Disambiguation	FF- D	FF D+1	FP D	FP D+1	GP D	GP D+1	SP/TT (any)	RO - D	RO - D+1	ALL
SCO/MCS	category	1, 13, 28, 97,		1, 13, 21, 22, 28, 60, 97,		29, 63, 64, 97,		29, 47, 63, 64	13, 21, 29, 31, 47,60, 97	63, 64	1, 13, 21, 22, 28, 29, 31, 47, 60, 63, 64, 97,
SCO/MCS	transitivity					97		1		97	1, 97
MC/RC	category	58, 65		6, 15, 19, 41, 56, 58, 65, 67, 69[1], 77, 94		15,		6, 19, 41, 48, 58. 77, 94	15, 41, 48, 56, 65, 67		6, 15, 19, 41, 48, 56, 58, 65, 67, 69, 77, 94
NP/S comp	category	20, 28, 65		28, 36, 42[2], 43, 65, 83, 93	63	83		63, 74, 83, 93	42[2], 65		20, 28, 36, 42, 43, 63, 65, 74, 83, 93
NP/S comp	casemarking	88		88							88
PP Attach	category			19				19			19
PP Attach	plausibility	31[3], 65[4]		10, 14, 31, 45, 46, 65, 76,	98	46	98	10, 46,	14, 31, 76	98	10, 14, 31, 45, 46, 56, 65, 76, 98
adverb attachment	morphology						54	54		54	54
adverb attachment	time adverb (plausibility)			4, 96		96			4		4, 96
RC attachment	plausibility			12[5]		45				90, 96[6]	12, 45, 90, 96
RC attachment	morphology (gender)			11, 100		11, 100		100			11, 32, 100
argument/ adjunct	plausibility			49			50	44, 50			44, 49, 50

Structure	Disambiguation	FF- D	FF D+1	FP D	FP D+1	GP D	GP D+1	SP/TT (any)	RO - D	RO - D+1	ALL
LDD	category + plausibility	89		89		62		61, 62		62[7]	61, 62, 89
NP/S coordination	category		80[8]	37, 80		80				80	37, 80
S/O RC	category			87		92		92	87, 92		87, 92
S/O RC	morphology			51			51[9]		38		38, 51
SC/RC	category			2, 3							2, 3

Note 1: SCO/MCS = initial subordinate clause object vs. main clause subject; MC/RC = main clause vs reduced relative clause; NP/S Comp = direct object NP vs sentence complement; PP attach = attach PP to verb or noun; adverb attach = attach adverb high or low; RC attach = attach relative clause to N1 or N2 in N1 of N2 construction; argument adjunct = analyze phrase as argument vs adjunct eg agentive-by vs. locative-by; LDD = long distance dependency (filler/gap); NP/S coordination = coordinate phrases as NP or as S; S/O RC = subject vs. object extracted relative clause.

Note 2: The following syntactic disambiguation experiments are unclassified:
8 lexical/syntactic category bias, FP effect, later modulated by context
16 NP conjunction, biased by pronoun or parallelism, late effects
24 sluicing, marginally faster with two than one possible antecedent
25 semantic (quantifier presupposition), FP and TT effects on D+1
26 conjoined NP, facilitated by parallelism, TT and marginal FP effects on D
29 Noun-noun compound vs noun-verb predication, delayed effect
39 Finnish, normal FP SVO preference overcome by casemarking
64 SCO/MCS French, really anaphora
82 apparent immediate interpretation of anaphor in coordinated VP, GP effect before end of VP

Note 3: Footnotes from table follow:

1. Reanalysis of 67, regression-contingent

3. Second language only
4. Significant when pooled over first 3 fixations
2. S-Comp slow regardless of ambiguity
5. English only
6. Ambiguous easier than disambiguated
7. Effect appeared at region D+2
8. D is the phrase "or NP" and D+1 is the following, truly disambiguating, region
9. Effect appeared at region D+2

Table 3: Classification of Articles Involving High-Order Effects other than Temporary Ambiguity (C = Critical Region)

Category	FF- C	FF C+1	FP C	FP C+1	GP C	GP C+1	SP/TT (any)	RO - C	RO - C+1	ALL
lexical predictability	35, 53, 72		5, 18[1], 35, 53, 72		5		72	5		5, 18, 35, 53, 72
semantic/pragmatic anomaly	55	71	9, 71, 85	57	71		71, 55, 85	57	71	9, 55, 57, 71, 85
syntactic anomaly			9, 17	59			59	9, 57, 59		9, 17, 57, 59
lexical semantics	33		33, 34	33, 34, 91	86		34, 85, 91	33, 34	86	33, 34, 86, 91
complexity	70, 80		40[2], 70, 80, 95		80		95	80		40, 70, 80, 95
syntactic category			78	78	78		75			75, 78
semantic interpretation - phrase and clause			7, 84, 99	27	84	52	23, 52, 73	7, 52	27	7, 23, 27, 52, 73, 84, 99

Note 1: Footnotes from table follow.

1. Also increased skipping of predictable word.

2. Also more fixations of complex region.

Figure 1: Regression-out Probability and Go-Past Time, Disambiguating Region; Data from Clifton et al. 2003, Pooled over Experiments 1 and 2