

1 **CHAPTER 49**2 **Syntactic influences on**  
3 **eye movements during**  
4 **reading**

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6 **Abstract**

7 Measuring where the eyes fixate, and for how long, has arguably been the most valuable way of  
8 exploring the time-course of comprehending written sentences. This chapter reviews some of the  
9 history of the method's use as well as some recent developments. It provides an extensive review of  
10 what eye movement measurement has told us about the syntactic processing of sentences, covering  
11 topics such as syntactic ambiguity, syntactic ambiguity resolution, retrieval from memory, syntactic  
12 prediction, and syntactic complexity. Alternative models for how syntactic and extra-syntactic infor-  
13 mation sources are integrated are discussed. The chapter then turns to a discussion of what the eyes  
14 actually do in response to syntactic processing complexity, and provides a brief review of models of  
15 eye movement control. It concludes by comparing eye movement measurement with other methods  
16 of measuring online sentence comprehension processes.

17 **Overview**

18 The use of eye movement monitoring to study sentence processing dates back to nearly the begin-  
19 ning of cognitive psychology. In 1967, Mehler et al. used a Mackworth camera to study where readers  
20 fixated when they read ambiguous sentences whose syntactic structures differed depending on the  
21 context that they appeared in. Consider the ambiguous sentence *They gave her dog candies*. When this  
22 occurred in a context about a girl who liked dog candies, the words *dog* and *candies* must be analysed  
23 together as a phrase (or constituent), *dog candies*. When the same sentence occurred in a context  
24 about a girl's dog, the words *her* and *dog* have to be analysed as a constituent, *her dog*. Mehler et al.  
25 (1967) found more frequent fixations on *dog* in the former case than in the latter case, which they  
26 interpreted to mean that readers tend to fixate a word more often when it begins a syntactic constitu-  
27 ent than when it terminates one.

28 The work that made eye tracking the 'gold standard' for studying visual sentence processing,  
29 however, appeared a decade and a half later. Frazier and Rayner (1982) used more modern equipment  
30 (a SRI dual-Purkinje tracker) that recorded fixation duration as well as position, and tested predic-  
31 tions of an explicit parsing theory (Frazier, 1978). They introduced the 'garden-path' theory of pars-  
32 ing, with the concepts of 'late closure' and 'minimal attachment'. This theory claims that readers and  
33 listeners use their implicit knowledge of phrase structure rules to build a syntactic tree. They apply

1 these rules in a parallel race, so that the first sequence of rules that succeeds in attaching an incoming  
 2 word into the current tree wins. This generally means that the simplest attachment, if there is one, is  
 3 created (minimal attachment), and if there is no most-simple attachment, then the winner is the one  
 4 that attaches the new material into the most available material, i.e. material currently being processed  
 5 (late closure). Frazier and Rayner were able to show that reading was disrupted when these strategies  
 6 led these readers ‘down the garden path,’ namely, when a temporary syntactic ambiguity was followed  
 7 by material that indicated that the minimal or late-closure attachment was incorrect. For instance,  
 8 readers showed long fixations and frequent regressions when a sentence fragment like *The girl knew*  
 9 *the answer continued was wrong*. Readers apparently took *the answer* to be the direct object and theme  
 10 of *know* (the syntactically minimal analysis) and were disrupted when they had to reanalyse it as the  
 11 subject of a complement sentence, *the answer was wrong*.

12 The Frazier and Rayner paper led to an outpouring of studies using eye tracking to study parsing  
 13 and sentence interpretation (see Clifton et al., 2007, for a review of 100 such studies). These studies  
 14 examined topics such as the effects of plausibility and discourse and referential context on syntactic  
 15 parsing, the detailed time course of parsing, and the fundamental architecture of the human sentence  
 16 processing mechanism.

17 Recent years have seen the development of innovative ways of using eye movements to study  
 18 sentence comprehension. Most early studies used sentences created for the purpose of testing specific  
 19 theoretical hypotheses, providing tight experimental control over important variables. Many research-  
 20 ers continue to create and study such sentences. However, some researchers have turned to measuring  
 21 eye movements while people read natural texts (e.g. Boston et al., 2008; Kennedy and Pynte, 2005).  
 22 There are clear costs and benefits to both the experimental and the ‘corpus-based’ approaches. The  
 23 latter approach certainly engages more normal comprehension processes, but at the cost of experi-  
 24 mental control of many factors known to affect eye movements (not the least of them, length and  
 25 frequency of words). One could hope that the two approaches will triangulate on the fundamental  
 26 processes underlying eye movements and sentence processing, but that hasn’t happened yet (cf. the  
 27 diverging evidence on whether the content of words in the parafoveal affects the duration of the current  
 28 fixation; Drieghe et al., 2008; Kennedy and Pynte, 2005; see also Drieghe, Chapter 46, this volume).

29 Another new development is the construction of explicit models of eye movement control (Engbert  
 30 et al., 2005; Pollatsek et al., 2006; Reichle et al., 1998, among others; see also Reichle, Chapter 42, and  
 31 Engbert and Kliegl, Chapter 43, this volume). These have greatly sharpened claims about the relation  
 32 between word recognition and eye movements, even if the disputes among competing claims have  
 33 not yet been resolved. However, extension of these models to questions of sentence parsing and  
 34 interpretation is still in its infancy; below we discuss the first, quite recent, attempt to account for  
 35 how the eyes respond to sentence processing difficulty within the framework of a lower-level model  
 36 of eye movement control (Reichle et al., 2009).

37 A third development that has had a great impact on language processing work is the measurement  
 38 of eye movements while one is listening to spoken language (Tanenhaus et al 1995; cf. Cooper, 1974).  
 39 Cooper’s early work indicated that people tended to look at things that were being talked about, and  
 40 that the eye movements were quite closely timelocked to speech. Tanenhaus et al. used this phenom-  
 41 enon to study the time course of word identification and sentence interpretation, and others have used  
 42 it to study a variety of topics in ambiguity resolution, anticipation of referents, and pragmatic constraints  
 43 on interpretation (Tanenhaus, 2007; see Henderson and Ferreira, 2004, for a collection of overview  
 44 chapters). In the remainder of this chapter, we will focus exclusively on the use of eye tracking in read-  
 45 ing; but cf. Altmann’s chapter in this volume (Chapter 54) for a survey of this ‘visual world’ research.

## 46 **Syntactic factors that affect eye movements in reading**

### 47 **Ambiguity effects**

48 A great many eye tracking studies have investigated sentences that are temporarily or permanently  
 49 ambiguous. Ambiguity is interesting in itself: it is pervasive in normal language use, but nonetheless

1 seems to cause little difficulty in communication. Somehow, readers are able to ‘see through’ the  
 2 ambiguity and determine the writer’s message. Presumably, they use discourse context, knowledge of  
 3 the writer (and of the writer’s knowledge), plausibility, and a great many other factors in resolving  
 4 ambiguity, seldom violating syntactic constraints (but cf. Ferreira, 2003; Sanford and Sturt, 2002, for  
 5 some evidence that people aren’t quite perfect).

6 One specific question that has attracted substantial attention is whether a reader entertains multi-  
 7 ple interpretations of an ambiguous sentence at one time, and if so, is there a cost to doing so.  
 8 Although existing theories take sharply different positions on the former question (e.g. Frazier and  
 9 Rayner, 1982; MacDonald et al., 1995), truly convincing evidence is lacking. However, the evidence  
 10 about the latter question is fairly clear: there does not seem to be an extra processing cost in the  
 11 ambiguous region when material is syntactically ambiguous (but see discussion of later costs when  
 12 the wrong analysis is made of the ambiguous region).

13 This answer is surprising, given the clear evidence that there is an extra cost in processing a lexi-  
 14 cally ambiguous item like *bark* than an unambiguous item, reflected in eye tracking measures during  
 15 reading (Duffy et al., 1988; cf. Juhasz and Pollatsek, Chapter 48, this volume). This extra cost can  
 16 plausibly be attributed to a time-consuming process of resolving the competition between the dog  
 17 sense and the tree sense of *bark*. However, there is essentially zero evidence that reading a syntacti-  
 18 cally ambiguous phrase is slower than reading an unambiguous one, when other factors are control-  
 19 led (see Clifton and Staub, 2008, for a thorough discussion). In fact, some ambiguous phrases are  
 20 actually read faster than their disambiguated counterparts (Traxler et al., 1998; van Gompel et al.,  
 21 2005). This fact can be taken as evidence against the claim that a reader chooses among multiple  
 22 interpretations of a sentence by activating them all and letting them compete for dominance (which  
 23 can be taken as an argument against the competitive multiple-analysis models to be discussed in the  
 24 next section). But it does not convincingly show that only a single interpretation is considered at a  
 25 time, since it is possible that multiple analyses are considered in a non-competitive, cost-free,  
 26 manner, perhaps in a ‘race’ to finding a single acceptable interpretation.

## 27 Garden-pathing

28 One line of evidence that a reader considers only a single interpretation at a time comes from studies  
 29 following up the original Frazier and Rayner (1982) garden-pathing findings. Frazier and Rayner  
 30 were interested in temporarily ambiguous sentences not just because of their ambiguity, but because  
 31 they argued that such sentences could be used to identify the decision processes a reader (or listener)  
 32 uses in understanding all kinds of sentences. When reading a sentence, a reader must decide  
 33 how each word fits into its sentence. The reader must build and interpret a mental representation of  
 34 the relations among words, and a great deal of evidence indicates that this takes place very quickly,  
 35 often even while the eyes are fixating on a word (Just and Carpenter, 1980; Rayner et al., 2004;  
 36 cf. Marslen-Wilson, 1973, for comparable evidence about listening).

37 The ‘garden-path’ model proposed by Frazier and Rayner was motivated by the assumption that a  
 38 reader had to have a representation of the structural relations among words in a sentence in order to  
 39 interpret it (*He gave her the dog candies* and *He gave her dog the candies* mean very different things,  
 40 which are dependent on the different syntactic structures of the two sentences). Sentences are inter-  
 41 preted nearly without delay, but their interpretation depends on a potentially-vast range of informa-  
 42 tion. If Frazier and Rayner are correct that sentences are not word salad, and that sentence  
 43 interpretations depend on how words are structurally related in a sentence, it would be very advanta-  
 44 geous for a reader or listener to build a syntactic structure as quickly as possible. Frazier and Rayner  
 45 favoured a model that claimed readers provisionally accept the very first structure they can build,  
 46 generally the simplest possible structure, so they quickly have *some* structure to interpret. Frazier and  
 47 Rayner’s eye tracking data showed disruptions of processing when material later in a sentence was  
 48 syntactically inconsistent with the simplest and most quickly built analysis of material earlier in the  
 49 sentence (and Rayner et al. (1983) showed similar effects when the later material was semantically  
 50 inconsistent with this structure). When a single word provides the disconfirmation, the disruption

1 can appear on the very first fixation on that word, as well as appearing as lengthened gaze durations  
 2 and increased frequency of regressions. When a multi-word region provides the disambiguation, the  
 3 latter two measures (and others, such as go-past time or regression path duration) generally reflect  
 4 the disruption (see Clifton et al., 2007, for discussion of how disruption appears in later published  
 5 research).

6 The early Frazier and Rayner work did have some notable shortcomings. For instance, their test of  
 7 minimal attachment (‘accept the simplest and therefore most quickly-built analysis’) compared  
 8 sentences like (1a) and (1b):

9 **1a.** The lawyers think his second wife will claim the inheritance.

10 **1b.** The second wife will claim the inheritance belongs to her.

11 They found that reading was disrupted on *belongs* in (1b) compared to earlier regions of the  
 12 sentence (presumably because readers took *the inheritance* to be the direct object of *claim*, not the  
 13 subject of a complement clause—a more complex, non-minimal, analysis). Clearly this is not an  
 14 ideal comparison: different words are being compared in different sentence contexts. Still, the basic  
 15 Frazier and Rayner findings have stood up (cf. Clifton et al., 2007, for a review). For instance, reading  
 16 of *belongs* is still disrupted in (1b) if it is compared to *The second wife will claim that the inheritance*  
 17 *belongs to her*, where *that* blocks the normally-preferred attachment (Rayner and Frazier, 1987).

18 Frazier and Rayner’s serial, single analysis, model provides an elegant account of their data, but it  
 19 nonetheless stimulated the development of several competing models. These models take issue with  
 20 the garden-path models on several major points: they propose that multiple syntactic analyses are  
 21 considered at once, not just a single analysis; they generally claim that semantic and pragmatic  
 22 factors, not just speed of construction, can affect which syntactic analysis is initially considered; and  
 23 some propose that these syntactic analyses are not built, following phrase structure rules, but instead  
 24 are activated from pre-existing structures in a mental store (see MacDonald et al., 1994; McRae et al.,  
 25 1998, for two of the most influential models). All these models are able to account for the basic  
 26 garden-pathing effects. All of them are able to account for the observation (e.g. Rayner et al., 1983)  
 27 that semantic effects can appear quite early in the eye tracking record. There have been lively disputes  
 28 about whether lexical or semantic or pragmatic factors can affect the initial choice of a syntactic  
 29 analysis or just the reanalysis of an initial, inappropriate analysis—two lines of research where the  
 30 advantage seems to shift from one side, to the other, and back again, can be found in Ferreira and  
 31 Henderson (1990), followed by Trueswell et al. (1993), then by Kennison, (2001); and in Ferreira and  
 32 Clifton (1986), followed by Trueswell et al. (1994), and then by Clifton et al., (2003).

33 It may turn out that convincing evidence can be provided showing that semantic or contextual  
 34 information can guide the parser’s initial choices, at least in the face of weak syntactic biases (Altmann  
 35 et al., 1998, and Britt, 1994, are apparent instances). But it may take other experimental paradigms  
 36 to answer the question of whether sentence comprehension is best thought of as a process of  
 37 constructing a syntactic analysis of a sentence and then using a wide range of semantic and contex-  
 38 tual information to interpret and correct this analysis, or a process of allowing this unconstrained  
 39 range of information to activate multiple possible analyses and eventually settle on a single one (cf.  
 40 Frazier, 1995, for discussion). From our admittedly-biased perspective, the current authors think  
 41 that it will be difficult to build a model that deals with the recovery from a garden path and the  
 42 processing of an ambiguity in the same competitive manner, given that the former disrupts reading  
 43 while the latter does not; but we acknowledge that not all the facts are in yet.

#### 44 **Memory effects**

45 There is more to sentence processing than ambiguity resolution. The very earliest psycholinguists  
 46 recognized that difficulty in understanding sentences should be attributed to memory or processing  
 47 resources being overloaded (Miller, 1962). It’s hard to understand *The rat that the cat that the*  
 48 *dog worried chased ate the malt*, perhaps because one has forgotten the first subject by the time  
 49 one reaches the final verb (or perhaps because processing too many subject–verb relations at once

1 overloads the system). Theorists have incorporated memory considerations into their processing  
 2 theories in various ways. Just and Carpenter (1980) proposed a model of language comprehension  
 3 and eye movements that made critical appeal to both short- and long-term memory processes in a  
 4 production model, and in later work (Just and Carpenter, 1992) focused on how individual differences  
 5 in working memory capacity affected eye movements in reading. Many researchers have examined  
 6 people with varying working memory spans, often measured using ‘reading span’ (Daneman and  
 7 Carpenter, 1980) They have found evidence that (e.g.) low-span readers use contextual or pragmatic  
 8 information less efficiently than high-span readers (Just and Carpenter, 1992; MacDonald et al.,  
 9 1992; Pearlmutter and MacDonald, 1995) (but cf. Waters and Caplan, 1996, for a critique of some of  
 10 this research).

11 Other researchers have concentrated on trying to develop explicit process models for how memory  
 12 might play a role in understanding sentences. Work by Gibson and his colleagues and students  
 13 (Gibson, 2000; Warren and Gibson, 2002) has been very influential. Although it has not yet resulted  
 14 in published studies of eye tracking during reading, its claim that the distance between dependent  
 15 elements (perhaps measured in terms of the number of new discourse entities introduced between  
 16 the elements) affects speed of comprehension has clear implications for eye tracking measures.  
 17 McElree and his colleagues (e.g. McElree et al., 2003) have developed models in which a content-  
 18 addressable memory search is involved in comprehending some sentence structures, but as in the  
 19 case of Gibson’s work, most of their research has used techniques other than eye tracking (but cf.  
 20 Martin and McElree, 2008, for an example of eye tracking research guided by considerations of  
 21 memory retrieval).

22 Perhaps the most complete and explicit theory of the roles that memory plays in sentence under-  
 23 standing is that of Lewis (cf. Lewis et al., 2006, for an accessible introduction). Once again, this  
 24 approach has not yet been tested extensively in eye tracking studies. However, some of its premises  
 25 have been supported in eye tracking research conducted by Gordon and colleagues (e.g. Gordon  
 26 et al., 2006). For example, these researchers argued that the difficulty of understanding an object  
 27 relative clause sentence like *The banker that the barber praised climbed the mountain just outside of*  
 28 *town* was due, at least in part, to interference from *barber* in retrieving the object of *praised*, namely,  
 29 *the banker*. Comparing these sentences to subject relative clause sentences (*The banker that praised*  
 30 *the barber . . .*), they found more regressive rereading after reaching the relative clause in sentences  
 31 like these than in sentences where the intervening noun phrase was a proper name (. . . *that Sophie*  
 32 *praised . . .*). Presumably, a proper name does not interfere as much with retrieval of the required  
 33 definite description, *the banker*, as another definite description would.

#### 34 Syntactic prediction

35 Several recent sentence processing models propose that the difficulty of incremental processing of  
 36 word-by-word input is a function of how predictable this input is, or more precisely, the probability  
 37 of the input given the sentence so far (Hale, 2001; Levy, 2008). These models assume that what  
 38 matters is not only the predictability of specific lexical items (as has been shown to affect eye move-  
 39 ments; Ehrlich and Rayner, 1981; Rayner et al., 2004; Rayner and Well, 1996), but also the predicta-  
 40 bility of syntactic structure. There is, in fact, eye movement evidence suggesting that material is read  
 41 more quickly in a context in which syntactic structure is highly predictable. For example, Staub and  
 42 Clifton (2006) demonstrated that when a disjunction is preceded by the word *either*, the material just  
 43 after the word *or* is read faster than when the word *either* is absent. Staub et al. (2006) also showed  
 44 that the direct object in a so-called ‘heavy NP shift’ structure (e.g. *Jack watched from the stands his*  
 45 *daughter’s attempt to shoot a basket.*) is read more quickly when the verb is obligatorily transitive,  
 46 which licenses a prediction of a shifted object (*Jack praised from the stands his daughter’s attempt to*  
 47 *shoot a basket*). Recently, Demberg and Keller (2009) and Boston et al. (2008) have shown, using  
 48 correlational methods, that a significant proportion of word-by-word reading time variance in  
 49 English and German eye movement corpora is explained by a surprisal metric based on the work of  
 50 Levy (2008) and Hale (2001). Finally, Staub (2010) has recently demonstrated that readers make

1 many regressive eye movements out of the subject of an object relative clause (e.g. *the fireman* in *The*  
 2 *employees that the fireman noticed hurried across the open field.*), which is claimed by the Hale/Levy  
 3 framework to be a point at which structural expectations are violated.

4 Another set of findings that may also be interpreted as reflecting syntactic prediction comes from  
 5 studies of the resolution of long-distance dependencies. It has been proposed that when the parser  
 6 encounters a constituent prior to the site of its interpretation (as in questions such as *Which puppy*  
 7 *did the girl buy?* and relative clauses such as *The puppy that the girl bought was a golden retriever.*) it  
 8 actively anticipates that this interpretation site will appear in the first grammatically licensed location  
 9 (De Vincenzi, 1991; Frazier and Flores D'Arcais, 1989). Several eye movement studies (Pickering and  
 10 Traxler, 2001, 2003; Staub, 2007; Traxler and Pickering, 1996) have contributed to a literature  
 11 confirming this principle. These studies have shown increased reading time when the first grammati-  
 12 cally licensed location turns out not to be correct, either because of an implausible verb-argument  
 13 relation (e.g. increased fixation durations on *landed* in *That's the truck that the pilot landed carefully*  
 14 *behind.*) or because this location turns out to be occupied by other material (e.g. increased  
 15 reading time on *a few pupils* in *That's the diver that the coach persuaded a few pupils to watch.*; cf.  
 16 Stowe, 1986).

### 17 Syntactic complexity

18 The findings reviewed to this point make it clear that some grammatical structures are more complex  
 19 than others to process in the sense of resulting in slower reading. Structures that result in garden  
 20 paths (i.e. disambiguated structures that require a reader to choose a normally-dispreferred analy-  
 21 sis), structures that place excessive demands on memory, structures that violate agreement or discon-  
 22 firm expectations—these are complex to process in this sense.

23 For present purposes, though, let us restrict 'syntactic complexity' to refer to some measure of the  
 24 complexity of linguistic structure or its derivational history (i.e. the series of underlying representa-  
 25 tions from which a surface form is thought to arise, on generative approaches to syntax). Returning  
 26 to the origins of psycholinguistics, the 'Derivational Theory of Complexity' claimed that increasing  
 27 the number of transformations involved in the derivation of a sentence (e.g. the transformation from  
 28 active to passive, or the transformation from an affirmative sentence to a negative one; Chomsky,  
 29 1957) increased its processing difficulty. This theory garnered some support (see Fodor et al., 1974,  
 30 for a review), for example from the fact that passive or negative sentences were harder to remember  
 31 than simple actives. However, linguistic theory itself soon adopted a conception of a sentence's deri-  
 32 vation that did not involve transformations in Chomsky's (1957) sense, and it soon became clear that  
 33 other explanations were available for the processing difficulty of transformationally-complex  
 34 sentences.

35 Perhaps complexity should, instead, be measured by number or density of syntactic nodes in the  
 36 kind of tree structure that syntacticians working within a generative grammar framework have been  
 37 using, in one form or another, since Chomsky (1957). Are structures that have greater syntactic  
 38 complexity, in this specific sense, read more slowly than structures with less complexity? Some  
 39 processing perspectives say they should be. If a reader builds up a tree structure by applying linguistic  
 40 rules or principles to the words in a sentence, and does so in a serial manner, one would expect that  
 41 more complex trees should result in slower reading time.

42 Indeed, there have been some sophisticated and promising analyses of the possible effects of syntac-  
 43 tic complexity (e.g. Frazier's, 1985, suggestion that complexity should be measured by how many  
 44 intermediate syntactic nodes have to be postulated essentially at once (e.g. within a window of no  
 45 more than three words)). However, there is precious little evidence from eye tracking or any other  
 46 technique that syntactic complexity slows reading. One source of evidence is Frazier and Rayner  
 47 (1988), who showed that eye tracking was disrupted in sentences that began with a sentential subject  
 48 (e.g. *That both of the Siamese twins survived the operation is remarkable*). Sentences like this require a  
 49 large amount of syntactic structure to be built up at the beginning of the subject (*That both . . .*), which  
 50 may be the source of their difficulty. However, they are also infrequent and they have an ambiguity

1 (whether *that* is a complementizer or a demonstrative) that lasts for only one word. At the present  
 2 time, it does not appear that there is clear evidence from eye tracking or elsewhere that increasing  
 3 syntactic complexity, without introducing additional parsing choices (temporary ambiguity) or  
 4 memory load, actually increases processing difficulty.

## 5 Syntactic violations

6 Using the event-related potential (ERP) paradigm, researchers have learned a great deal about how  
 7 the brain responds to syntactic violations (see Kutas et al., 2006, for a recent review). It is perhaps  
 8 surprising that the use of violations has been relatively rare in the eye movement literature, until one  
 9 considers that one of the great attractions of the eye movement paradigm has always been its ability  
 10 to capture language processing under natural conditions. Nevertheless, there are a few studies that  
 11 have examined how the eyes respond when they encounter either a phrase structure violation or an  
 12 agreement violation (Braze et al., 2002; Deutsch and Bentin, 2001; Ni et al., 1998; Pearlmutter et al.,  
 13 1999). These studies vary in when the effect of anomaly first appears in the eye movement record,  
 14 with two of the studies (Ni et al., 1998, Pearlmutter et al., 1999) failing to find first pass reading time  
 15 effects on the critical word. Clearly, more work is required in this area.

## 16 What do the eyes do when there are syntactic processing 17 problems?

### 18 How quickly do syntactic processing problems appear in the eye movement 19 record?

20 Important properties of lexical items, such as their frequency of occurrence and their predictability  
 21 in context, affect the time taken to read them in a rather uniform fashion (see Staub and Rayner,  
 22 2007, for a review). The effects of these properties consistently appear in such measures as first  
 23 fixation duration and gaze duration. Some exceptions do exist—e.g. less-skilled readers, upon  
 24 encountering an infrequent and unpredicted word in a context that strongly predicts a different and  
 25 more common word, do tend to fixate it relatively briefly, perhaps not even encoding the word  
 26 (Ashby et al., 2005)—but they are exceptions.

27 In contrast, effects of syntactic processing difficulty can show up at various points in the eye track-  
 28 ing record. In the original Frazier and Rayner (1982) study, disruption appeared as an apparent  
 29 lengthening of the very first fixation on the region that disambiguated a sentence to its unpreferred  
 30 syntactic analysis. Other studies (e.g. Staub, 2007) have also shown first fixation effects. But effects of  
 31 syntactic processing often do not appear this quickly. In many cases, the disambiguating information  
 32 is spread out over a multi-word region, and in these cases, one could not expect a first fixation effect.  
 33 But although effects quite often show up as increases in first pass reading times, they sometimes only  
 34 show up as an increased frequency of regressions, or as an increased go-past/cumulative region read-  
 35 ing time, or even only as an increased time in the following (spillover) region or as increased second  
 36 pass time. Clifton et al. (2007) listed studies showing each of these patterns of effects, but were unable  
 37 to pinpoint factors that determined which pattern would appear. Some potentially contributing  
 38 factors might be the type of ambiguity or syntactic difficulty, or how it is disambiguated, or the  
 39 reading goals of a subject, or the subject's reading skill, or other factors not yet identified. While there  
 40 is a substantial amount of work investigating the factors that influence the amount of syntactic  
 41 processing difficulty that appears in the eye movement record, and there is interesting work on  
 42 the process of how a syntactic misanalysis is reanalysed (see Fodor and Ferreira, 1998, for a useful  
 43 overview), very little work has been done investigating how various factors influence the precise  
 44 timing at which syntactic difficulty first appears in the eye movement record. As pointed out by,  
 45 e.g. Bornkessel and Schlesewsky (2006), the very existence of first fixation effects of syntactic process-  
 46 ing difficulty is superficially inconsistent with the fact that such effects tend to show up later in the

- 1 electroencephalography (EEG) record, but this may turn out to be a limitation of existing analyses of
- 2 EEG (cf. Sereno and Rayner, 2003).

### 3 The tradeoff problem and distributional effects

4 One interesting empirical question that has been addressed is whether there is a tradeoff between  
 5 fixating a longer time on a region (e.g. a disambiguating region) and regressing to an earlier part of  
 6 the sentence. A series of exchanges between Altmann and his colleagues, on the one hand, and Rayner  
 7 and Sereno, on the other, is illuminating if less than conclusive (Altmann, 1994; Altmann et al., 1992;  
 8 Rayner and Sereno 1994a, 1994b). Altmann observed that fixations made prior to a regression out of  
 9 a word were, for the most part, shorter than fixations made prior to a forward saccade.<sup>1</sup> When a  
 10 garden-path sentence (a reduced relative clause sentence) was presented by itself, the disruption  
 11 observed in first pass time in the disambiguating region was at least as large when a fixation in this  
 12 region was followed by a forward saccade as when it was followed by a regression. But interestingly,  
 13 he found that when the temporarily ambiguous sentence was presented with a preceding context that  
 14 biased toward the relative clause reading (by introducing two possible referents named by the same  
 15 word, so that modification was needed to avoid referential failure), garden-path disruption of first  
 16 pass time appeared only on trials on which there was a regression out of the disambiguating region.  
 17 This does not suggest a tradeoff between regressions and lengthened fixations, but instead, suggests  
 18 that reading time was affected only on those trials where comprehension was disrupted so much that  
 19 a regression was made.

20 Rayner and Sereno, in contrast, analysed data in which a discourse context appeared to have only  
 21 delayed, not immediate, effects on comprehension difficulty. They found a numerically larger effect  
 22 of garden-pathing when there was no regression out of the disambiguating region than when there  
 23 was a regression. This pattern, which Rayner and Sereno appeared to believe is typical of eye tracking  
 24 data (and was true of data for sentences without preceding contexts presented by Altmann et al.,  
 25 1992), suggests that there may in fact be a tradeoff between longer fixations and regressions. However,  
 26 it is not yet clear when this tradeoff occurs or what factors govern the choice (stay or look back) that  
 27 is made.

28 A related issue, and one which is critical for distinguishing between parsing theories, is whether  
 29 syntactic processing difficulty is manifested as an all-or-none phenomenon. According to serial  
 30 accounts like the garden-path theory (Frazier, 1987; Frazier and Rayner, 1982) and the unrestricted  
 31 race model (Van Gompel et al., 2005), reading times at a potential point of difficulty should be bimo-  
 32 dally distributed: if the reader was maintaining the correct parse at the point of encountering the  
 33 critical input, no difficulty should be evident, but if the reader was maintaining an incorrect parse,  
 34 rather extreme difficulty associated with syntactic revision should appear. On the other hand, a spate  
 35 of both older (McRae et al., 1998) and more recent (Levy, 2008) parsing models predict that syntactic  
 36 processing difficulty should be graded, with the amount of difficulty reflecting the amount of required  
 37 updating of activation levels associated with multiple candidate analyses. Thus, these models would  
 38 not seem to predict bimodality. We believe that the distributions of fixation durations under differ-  
 39 ent experimental conditions deserve close examination. A promising beginning (limited to lexical  
 40 variables) can be seen in Staub et al. (2010), who recently carried out formal analyses of distributions  
 41 of fixation durations, focusing on the distributional effects of word frequency. Staub et al. showed  
 42 that fixations are longer on essentially all trials when a word is low in frequency (a shift effect), but  
 43 that the longest fixations were especially lengthened (a skew effect). However, Staub (submitted) has  
 44 recently found that a lexical predictability manipulation results in a shift effect, but no skew effect.  
 45 This suggests that word frequency predictability affect fixation durations via different mechanisms.

AQ: please update Staub (submitted) if now in press or published

<sup>1</sup> We note that Mitchell and Shen (in press) have recently replicated this observation, and have shown how it is actually predicted by the latest iteration of the E-Z Reader model (Reichle et al., 2009).

1 Similar analyses of the effects of syntactic and other high-level variables may well shed light on their  
2 mechanisms.

### 3 Targeting of regressions

4 When a regression is made, what controls its target? Most regressions are, in all likelihood, simply  
5 corrections of misplaced landing positions, and therefore cover only a short distance and do not  
6 provide information about parsing (see Mitchell et al., 2008, for relevant discussion). However, it is  
7 possible that some regressions can shed light on the process of sentence comprehension.

8 Frazier and Rayner (1982) analysed regressions, and reported that they frequently went from the  
9 disambiguating region to the earlier point of ambiguity. However, as Mitchell et al. have pointed out,  
10 the point of ambiguity was often only one or two words before the disambiguation. While it is  
11 informative that regressions did not often return to the start of the sentence, suggesting starting over  
12 from scratch after a garden-path, the Frazier and Rayner data need not be taken as clear evidence for  
13 intelligently-directed regressions.

14 A report by Meseguer et al. (2002) provides more convincing data. Their Spanish readers were  
15 likely to regress from the verb of an adverbial phrase when the form of this verb (indicative vs.  
16 subjunctive mood) forced the adverbial phrase to be attached high, modifying the first verb of the  
17 sentence, and prevented the normally-preferred low-attachment analysis. More critically, the relative  
18 frequency with which a regression from this sentence-final verb landed specifically on the first verb  
19 was greater when the sentence was disambiguated toward the normally-unpreferred than the normally-  
20 preferred analysis. This does suggest intelligent guidance of regressions. However, the differential  
21 frequency of such verb-directed regressions was quite small, only a few percentage points, and (as  
22 Mitchell et al., 2008, suggest), it may matter that the regressions were launched from the last word in  
23 the sentence, given that regressions from a sentence-final word are quite frequent in any event.

24 Mitchell et al. (2008) present the most extensive available analysis of the targeting of regressions.  
25 They examined regressions out of the disambiguating region of English late closure sentences similar  
26 to those studied by Frazier and Rayner (1982) (e.g. . . . *while the men hunted the moose that was sturdy*  
27 *and nimble hurried into the woods . . .*). They found relatively few immediate regressions directly to the  
28 ambiguous region (the initial verb *hunted* and its apparent direct object *the moose*). However, they  
29 did find a substantial number of returns to this region in the first few regressive saccades after the  
30 disambiguating region. This suggests that regressive eye movements may be guided intelligently,  
31 perhaps a bit sluggishly or (following Inhoff and Weger, 2005) perhaps guided by an imperfect  
32 memory for the position of the ambiguity.

### 33 Models of eye movement control and models of sentence 34 processing

35 Models of eye movement control in reading have achieved a very high degree of sophistication, with  
36 the E-Z Reader (Pollatsek et al., 2006; Reichle, Chapter 42, this volume) and SWIFT (Engbert et al.,  
37 2005; Engbert and Kliegl, this volume) models each accounting for a wide range of findings regard-  
38 ing factors that influence the duration and location of readers' eye fixations. In both models, percep-  
39 tual processing, attentional factors, lexical processing, and oculomotor factors combine (in different  
40 ways in the two models) to produce the observed pattern of eye movement behaviour. However, a  
41 widely acknowledged shortcoming of these models is that they do not model the effects of linguistic  
42 processing above the level of the word. For example, until recently E-Z Reader made no attempt at  
43 all to explain inter-word regressions, and while SWIFT does allow for such regressions, it explains  
44 them on the basis of incomplete lexical processing of a word that the eyes have already left. Neither  
45 model was designed to deal with the fact that difficult syntactic processing inflates reading times and/  
46 or causes an increase in the likelihood of a regressive eye movement.

47 Recently, however, Reichle et al. (2009) have attempted to remedy this situation by modifying the  
48 architecture of E-Z Reader. The critical addition is a 'post-lexical integration' stage of processing of

1 word  $n$  that runs concurrently with the shift of attention to word  $n+1$ , and then with processing of  
 2 that word. If integration of word  $n$  fails rapidly enough, the forward saccade to word  $n+1$  is cancelled,  
 3 resulting in an increased fixation duration on word  $n$ , a refixation of word  $n$ , or a regression. If inte-  
 4 gration of word  $n$  fails more slowly, and the eyes have already moved to word  $n+1$ , a regressive eye  
 5 movement ensues. There are various details in Reichle et al.'s (2009) proposal that are open to debate,  
 6 such as the assumption of strictly serial lexical and syntactic processing, and the assumption that  
 7 syntactic processing only intrudes on the normal sequence of eye movements when a parsing break-  
 8 down has occurred. Nevertheless, we think that the integration stage in the Reichle et al. model is a  
 9 major step forward, for it is the first serious attempt to integrate several decades of research on the  
 10 effects of syntactic processing on eye movements into an implemented model of eye movement  
 11 control in reading that also takes serious account of lower-level factors.

12 There have also been some attempts to make explicit the mapping between processing stages and  
 13 eye movement measures that have started from a detailed parsing model rather than from a detailed  
 14 model of eye movement control. In these cases, theorists have asked whether the kinds of processing  
 15 operations proposed by a parsing model (e.g. attaching a word into the phrase marker, checking  
 16 agreement, checking binding relations, retrieving a head or dependent from memory) can be mapped  
 17 onto specific eye movement measures. For example, Boland (2004) has claimed that 'the eyes do not  
 18 leave a word until it has been structurally integrated. Therefore, constraints that control structure-  
 19 building influence first-pass reading time' (p. 60). An obvious problem with this proposal is the  
 20 presence of spillover effects where difficulty associated with attaching a word or phrase appears only  
 21 downstream of the word or phrase itself (see Clifton et al., 2007, for examples). More recently,  
 22 Vasishth et al. (2008) have suggested that the time needed for memory retrieval in the course of  
 23 sentence processing is reflected most closely in rereading time (i.e. second-pass time), which is the  
 24 sum of fixations on a word or phrase after the word or phrase is first exited. While Vasishth et al.  
 25 demonstrate an impressively tight link between the predictions of their memory retrieval model and  
 26 empirical rereading times, their analysis faces a serious conceptual problem, as their re-reading time  
 27 measure was based only on trials on which rereading actually occurred (usually a minority of trials),  
 28 while the model was designed to predict memory retrieval time in general. Clearly, more work  
 29 remains to be done in this domain.

### 30 **Eye tracking, self-paced reading, and event-related potentials:** 31 **comparison and contrast**

32 In this section, we consider how eye tracking compares to the other dominant paradigms for study-  
 33 ing on-line syntactic processing: self-paced reading (SPR) and ERPs. There are important practical  
 34 issues involved in the choice between these paradigms, with eye tracking falling somewhere between  
 35 the other two methods in terms of cost and in terms of complexity of the data analysis process. Here,  
 36 however, we focus on a more substantive issue: what kind of inferences about 'normal' syntactic  
 37 processing is it possible to draw based on results from the three paradigms?

38 In the SPR paradigm (Just et al., 1982; cf. Mitchell, 2004), a sentence is revealed on a computer  
 39 screen one word, or phrase, at a time. The rate at which the sentence is revealed is under the control  
 40 of the experimental subject, who repeatedly presses a key to reveal each word or phrase. While  
 41 'cumulative' versions of this paradigm have been used (Just et al., 1982), it is by far more common to  
 42 use a 'non-cumulative' version, in which only one word or phrase is visible, with preceding regions  
 43 being masked when a new region is displayed. The dependent measure in SPR is the latency of  
 44 button-pressing; it is assumed that as processing becomes difficult, subjects will slow down their rate  
 45 of button-pressing, in a manner analogous to the way in which, in normal reading, the eyes tend to  
 46 rest longer before moving past a difficult-to-process word or region.

47 An enormous amount of sentence processing research has been carried out using SPR (see Mitchell,  
 48 2004, for a review), and even more strikingly, implemented computational models of syntactic  
 49 processing have often been tested against SPR data (Levy, 2008; McRae et al., 1998; Tabor and

1 Hutchins, 2004.). In our view, this state of affairs is rather problematic. Our main reason for worry  
 2 is that little is known about how three critical aspects of the SPR task might affect patterns of experi-  
 3 mental results.

4 First, SPR tends to be quite slow compared to normal reading: In the word-by-word variant of  
 5 SPR, readers may spend up to twice as long on a word as they would in normal reading (though there  
 6 is a great deal of variability in SPR times obtained in different experiments, and in different labs).  
 7 Thus, readers have a substantial amount of ‘unallocated’ time (i.e. time not used in the service of  
 8 word recognition or eye movement control) in which to process the input material. This time may  
 9 be used to entertain competing syntactic analyses, make predictions, etc. We do not think it is safe to  
 10 assume that syntactic processing during slowed-down reading is similar in all relevant respects to  
 11 syntactic processing during normal reading. Second, in the non-cumulative version of SPR (which is  
 12 by far the dominant version) readers cannot look back at earlier regions of the sentence. Thus, the  
 13 ‘external memory’ that the text provides is not available, and again, it is difficult to say how this  
 14 might affect processing strategies. (It could be argued that SPR mimics auditory language processing  
 15 in terms of the lack of a continuously existing external representation of the sentence.) Finally, and  
 16 perhaps most importantly, SPR substitutes a consciously-controlled, newly-learned method of  
 17 progressing through a sentence for the relatively automatic, highly-practised skill of moving one’s  
 18 eyes. Again, it is impossible to know how this substitution might affect data patterns. Models of eye  
 19 movement control in reading have made great progress in accounting for variance in fixation dura-  
 20 tions and saccade landing positions based on the assumption that readers’ eye movements are trig-  
 21 gered by a combination of low-level oculomotor routines and ongoing lexical processing. While  
 22 higher-level linguistic processing, such as syntactic processing, clearly does affect patterns of eye  
 23 movements, it appears to do so in a relatively circumscribed manner. Indeed, the initial E-Z Reader  
 24 model adopted the assumption that ‘higher-order processes intervene in eye-movement control only  
 25 when “something is wrong” and either send a signal to stop moving forward or a signal to execute a  
 26 regression’ (Reichle et al., 1998, p. 450). However, when a reader must make a conscious decision to  
 27 press a button to receive the next input word, a very different balance of factors may be at work; it is  
 28 within the reader’s conscious control (as opposed to the control of highly automatized processing  
 29 system) to decide what criteria to use for pressing the spacebar. In sum, we think that the time has  
 30 come for the field to undertake a serious analysis of SPR as a task, to investigate how its demands do  
 31 (or more happily, do not) modulate normal processing.

32 In ERP research (see Kutas et al., 2006, for an overview), electrophysiological activity at the scalp  
 33 is measured, time-locked to the presentation of a visual or auditory stimulus. In the majority of ERP  
 34 experiments on sentence processing, sentences are presented visually, one word at a time, using the  
 35 rapid visual serial presentation (RSVP) paradigm, and the response to a critical word is measured.  
 36 Often, the critical word is the last word of the stimulus, and as noted above, this word often consti-  
 37 tutes a violation of some sort (i.e. either semantic or syntactic).

38 In our view, ERP research provides a very useful complement to eye tracking, as the two paradigms  
 39 provide distinct types of information. ERP research has distinguished qualitatively distinct electro-  
 40 physiological responses to different types of linguistic violations, with different latencies, different  
 41 scalp locations, and different polarities. For example, syntactic and semantic violations have different  
 42 ERP signatures. Encountering a semantically anomalous but syntactically licensed word in a sentence  
 43 leads to an increase in the amplitude of a negative electrical potential that peaks about 400 ms after  
 44 word onset (the N400). In contrast, syntactic violations, depending on their type, may lead either to  
 45 a left-lateralized negativity in the same time range (the left anterior negativity, or LAN) or to modu-  
 46 lation of a later, positive component (the P600); see, e.g. Bornkessel-Schlesewsky and Schlewsky  
 47 2009. However, these effects are indeed qualitatively distinct, so it is difficult to draw conclu-  
 48 sions about the relative amount of difficulty induced by different manipulations. Moreover, it is  
 49 notoriously problematic to draw conclusions about cognitive timing based on the latency of ERP  
 50 effects. With eye tracking data, on the other hand, it is more straightforward to assess the relative  
 51 amount of difficulty induced by an experimental manipulation, and timing is relatively (though not  
 52 completely) transparent. But with eye tracking data, it is more difficult to tell different kinds of

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 the Bornkessel-  
 Schlewsky and  
 Schlewsky, 2009  
 reference

1 processing apart: all difficulty appears in the form of a slowdown and/or an increase in the likelihood  
2 of a regressive eye movement.

3 As with SPR, one drawback of ERP is artificial stimulus presentation. Recently, a few labs have  
4 begun recording EEG during normal reading, with the ultimate goal of establishing correspondence  
5 between eye movement behaviour and events in the electrophysiological record (e.g. Dimigen et al.,  
6 2007; Kretzschmar, 2010). This is technically very challenging, not least because eye movements and  
7 blinks induce artefacts in the EEG record, but we think that this is a very promising line of future  
8 research. And, somewhat as compensation, it is possible to time-lock the EEG signal to the onset of  
9 auditory words, so ERPs can be used to directly investigate the similarities and differences between  
10 auditory and visual processing of linguistic input.

11 In sum, we think that the artificial modes of stimulus presentation used in ERP and SPR need to  
12 be taken into account in interpreting reading data from these paradigms. We think that the ability of  
13 the ERP paradigm to elucidate qualitative distinctions between brain responses, and to enable  
14 comparisons between visual and auditory processing, are clear advantages of this paradigm. We are  
15 somewhat less certain whether there are advantages to SPR studies, especially now that eye tracking  
16 technology has become relatively inexpensive and user-friendly, though we do acknowledge that  
17 many very important contributions to the study of sentence processing (e.g. the work of Gibson,  
18 2000, and his colleagues, as well as earlier work reviewed by Mitchell, 2004) have been made by SPR  
19 studies.

## 20 **Summary and conclusions**

21 In this chapter, we have attempted to provide an overview of the kinds of questions about syntactic  
22 processing that eye movement research has been used to answer, and to provide a general sense of  
23 some of the answers to these questions. Obviously, we have only scratched the surface, and the inter-  
24 ested reader is directed to the literature cited here. Looking at things the ‘other way around,’ we have  
25 also tried to point out some of the unresolved questions about how the eyes respond to syntactic  
26 processing difficulty, and about how syntactic processing should be integrated into full models of eye  
27 movement control in reading. We hope the reader takes away from this an appreciation both of how  
28 much has been learned from eye movement studies of syntactic processing, and of how much remains  
29 to be done.

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