CHAPTER 49

Syntactic influences on eye movements during reading

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Abstract

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

Overview

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

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

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

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

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

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

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

Syntactic factors that affect eye movements in reading

Ambiguity effects

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

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

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

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

Garden-pathing

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

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

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

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

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

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

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

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

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

Memory effects

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

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

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

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

Syntactic prediction

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

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

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

Syntactic complexity

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

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

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

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

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

Syntactic violations

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

What do the eyes do when there are syntactic processing problems?

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

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

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

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

The tradeoff problem and distributional effects

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

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

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

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[1] 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).

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

Targeting of regressions

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

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

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

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

Models of eye movement control and models of sentence processing

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

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

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

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

Eye tracking, self-paced reading, and event-related potentials: comparison and contrast

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

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

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

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

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

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

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

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

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

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

Summary and conclusions

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

Acknowledgements

Please send correspondence to Charles Clifton (cec@psych.umass.edu) or Adrian Staub (astaub@psych.umass.edu). We would like to thank Lyn Frazier and Keith Rayner for their comments on an earlier version of this manuscript. Preparation of the manuscript was supported in part by Grant HD-18708 from the National Institute for Child Health and Human Development. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institute for Child Health and Human Development or the National Institutes of Health.

References

Altmann, G.T.M. (1994). Regression-contingent analyses of eye movements during sentence processing: Reply to Rayner and Sereno. *Memory and Cognition*, **22**, 286–290.

Altmann, G.T.M., Garnham, A., and Dennis, Y. (1992). Avoiding the garden path: Eye movements in context. *Journal of Memory and Language*, **31**, 685–712.

Altmann, G.T.M., van Nice, K.Y., Garnham, A., and Henstra, J.-A. (1998). Late closure in context. *Journal of Memory and Language*, **38**, 459–484.

Ashby, J., Rayner, K., and Clifton, C.J. (2005). Eye movements of highly skilled and average readers: Differential effects of frequency and predictability. *Quarterly Journal of Experimental Psychology*, **58A**, 1065–1086.

Boland, J. (2004). Linking eye movements to sentence comprehension in reading and listening. In M. Carreiras and C. Clifton Jr (eds.) *The on-line study of sentence comprehension* (pp. 51–76). New York: Psychology Press.

49-Liversedge-49.indd 906 4/14/2011 5:23:51 PM

Bornkessel, I. and Schlesewski, M. (2006). The extended argument dependency model: A neurocognitive approach to sentence comprehension across languages. *Psychological Review*, **113**, 787–821.

Boston, M.F., Hale, J., Kliegl, R., Patil, U., and Vasishth, S. (2008). Parsing costs as predictors of reading difficulty: An evaluation using the Potsdam Sentence Corpus. *Journal of Eye Movement Research*, 1–19.

Britt, M.A. (1994). The interaction of referential ambiguity and argument structure in the parsing of prepositional phrases. *Journal of Memory and Language,* **33**, 251–283.

Braze, D., Shankweiler, D., Ni, W., and Palumbo, L.C. (2002). Readers' eye movements distinguish anomalies of form and content. *Journal of Psycholinguistic Research*, **31**, 25–45.

Chomsky, N. (1957). *Syntactic structures*. The Hague: Mouton.

Clifton, C. Jr. and Staub, A. (2008). Parallelism and competition in syntactic ambiguity resolution. *Language and Linguistics Compass*, **2**, 234–250.

Clifton, C. Jr, Staub, A., and Rayner, K. (2007). Eye movements in reading words and sentences. In R.V. Gompel and M. Fisher and W. Murray and R.L. Hill (eds.) *Eye movement research: Insights into mind and brain* (pp. 341–371). New York: Elsevier.

Clifton, C. Jr., Traxler, M., Mohamed, M.T., Williams, R.S., Morris, R.K., and Rayner, K. (2003). The use of thematic role information in parsing: Syntactic processing autonomy revisited. *Journal of Memory and Language*, **49**, 317–334.

Cooper, R.M. (1974). The control of eye fixation by the meaning of spoken language: A new methodology for the real-time investigation of speech perception, memory, and language processing. *Cognitive Psychology*, **6**, 84–107.

Daneman, M. and Carpenter, P. (1980). Individual differences in working memory and reading. *Journal of Verbal Learning and Verbal Behavior*, **19**, 450–466.

Demberg, V. and Keller, F. (2009). Data from eye-tracking corpora as evidence for theories of syntactic processing complexity. *Cognition,* **109**, 193–210.

Deutsch, A. and Bentin., S. (2001). Syntactic and semantic factors in processing gender agreement in Hebrew: Evidence from ERPs and eye movement. *Journal of Memory and Language*, **45**, 200–224.

DeVincenzi, M. (1991). *Syntactic parsing strategies in Italian*. Dordrecht: Kluwer Academic Publishers.

Dimigen, O., Sommer, W., Dambacher, M., and Kliegl, R. (2007). Co-registration of eye movements and event-related brain potentials: A new tool to investigate eye movement control in reading. Paper presented at the 14th European Conference on Eye Movements, Potsdam, Germany.

Drieghe, D., Rayner, K., and Pollatsek, A. (2008). Mislocated fixations can account for parafoveal-on-foveal effects in eye movements in reading. *Quarterly Journal of Experimental Psychology*, **61**, 1239–1249.

Duffy, S.A., Morris, R.K., and Rayner, K. (1988). Lexical ambiguity and fixation times in reading. *Journal of Memory and Language*, **27**, 429–446.

Ehrlich, S.F. and Rayner, K. (1981). Contextual effects on word perception and eye movements during reading. *Journal of verbal Learning and verbal Behavior*, **20**, 641–655.

Engbert, R., Nuthmann, A., Richter, E.M., and Kliegl, R. (2005). SWIFT: A dynamical model of saccade generation during reading. *Psychological Review*, **112**, 777–813.

Ferreira, F. (2003). The misinterpretation of noncanonical sentences. *Cognitive Psychology*, **47**, 164–203.

Ferreira, F. and Clifton, C., Jr (1986). The independence of syntactic processing. *Journal of Memory and Language*, **25**(3), 348–368.

Ferreira, F. and Henderson, J. (1990). The use of verb information in syntactic parsing: Evidence from eye movements and word-by-word self-paced reading. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, **16**, 555–568.

Fodor, J.D. and Ferreira, F. (Eds). (1998). *Sentence reanalysis*. Dordrecht: Kluwer Academic Publishers.

Fodor, J.A., Bever, T.G., and Garrett, M.F. (1974). *The psychology of language: An introduction to psycholinguistics and generative grammar*. New York: McGraw-Hill.

Frazier, L. (1985). Syntactic complexity. In D. Dowty and L. Kartunnen and A. Zwicky (eds.) *Natural language parsing* (pp. 129–189). Cambridge: Cambridge University Press.

Frazier, L. (1978). On comprehending sentences: Syntactic parsing strategies. Unpublished doctoral dissertation, University of Connecticut.

Frazier, L. (1987). Sentence processing: A tutorial review. In M. Coltheart (ed.) *Attention and performance* (pp. 559–586). Hillsdale, NJ: Lawrence Erlbaum Associates.

Frazier, L. (1995). Constraint satisfaction as a theory of sentence processing. *Journal of Psycholinguistic Research*, **24**, 437–468.

Frazier, L. and Rayner, K. (1982). Making and correcting errors during sentence comprehension: Eye movements in the analysis of structurally ambiguous sentences. *Cognitive Psychology*, **14**, 178–210.

Frazier, L. and Rayner, K. (1988). Parameterizing the language processing system: Left- vs. right-branching within and across languages. In J.A. Hawkins (ed.) *Explaining Language Universals* (pp. 247–279). Oxford: Basil Blackwell.

Frazier, L., and Flores d'Arcais, G.B. (1989). Filler driven parsing: A study of gap filling in Dutch. *Journal of Memory and Language*, **28**, 331–344.

Gibson, E. (2000). The dependency-locality theory: A distance-based theory of linguistic complexity. In Y. Miyashita and A.P. Marantz and W. O'Neill (eds.) *Image, Language, Brain*. Cambridge, MA: MIT Press.

Gordon, P.C., Hendrick, R., Johnson, M., and Lee, Y. (2006). Similarity-based interference during language comprehension: Evidence from eye-tracking. *Journal of Experimental Psychology: Learning, Memory and Cognition*, **32**, 1304–1321.

OUP UNCORRECTED PROOF – FIRST-PROOF, 14/04/2011, GLYPH

Hale, J. (2001). A probabilistic Earley parser as a psycholinguistic model. *Proceedings of NAACL*, **2**, 159–166.
Henderson, J.M. and Ferreira, F. (eds.) (2004). *The interface of language, vision, and action: Eye movements and the visual world*. New York: Psychology Press.
Inhoff, A.W. and Weger, U.W. (2005). Memory for word location during reading: Eye movements to previously read words are spatially selective but not precise. *Memory and Cognition*, **33**, 447–461.
Just, M.A. and Carpenter, P. (1980). A theory of reading: From eye fixations to comprehension. *Psychological Review*, **85**, 109–130.
Just, M.A. and Carpenter, P.A. (1992). A capacity theory of comprehension: Individual differences in working memory. *Psychological Review*, **99**, 122–149.
Just, M.A., Carpenter, P.A., and Woolley, J.D. (1982). Paradigms and processes in reading comprehension. *Journal of Experimental Psychology: General*, **111**, 228–238.
Kennedy, A. and Pynte, J. (2005). Parafoveal-on-foveal effects in normal reading. *Vision Research*, **45**, 153–168.
Kennison, S.M. (2001). Limitations on the use of verb information during sentence comprehension. *Psychonomic Bulletin and Review*, **8**, 132–137.
Kretzschmar, F. (2010). The electrophysiological reality of parafoveal processing: On the validity of language-related ERPs in natural reading. Unpublished Doctoral Dissertation, University of Mainz.
Kutas, M., Van Petten, C., and Kluender, R. (2006). Psycholinguistics electrified II (1994–2005). In M.A. Gernsbacher and M. Traxler (eds.) *Handbook of psycholinguistics* (2nd edn.) (pp. 655–720). New York: Elsevier.
Levy, R. (2008). Expectation-based syntactic comprehension. *Cognition*, **106**, 1126–1177.
Lewis, R.L., Vasishth, S., and Van Dyke, J.A. (2006). Computational principles of working memory in sentence comprehension. *Trends in Cognitive Sciences*, **10**, 447–454.
Martin, A. and McElree, B. (2008). A content-addressable pointer mechanism underlies comprehension of verb phrase ellipsis. *Journal of Memory and Language*, **58**, 879–906.
McElree, B., Foraker, S., and Dyer, L. (2003). Memory structures that subserve sentence comprehension. *Journal of Memory and Language*, **48**, 67–91.
MacDonald, M.D., Just, M.A., and Carpenter, P.A. (1992). Working memory constraints on the processing of syntactic ambiguity. *Cognitive Psychology*, **24**, 56–98.
MacDonald, M.C., Pearlmutter, N.J., and Seidenberg, M.S. (1994). The lexical nature of syntactic ambiguity resolution. *Psychological Review*, **101**, 676–703.
Marslen-Wilson, W.D. (1973). Linguistic structure and speech shadowing at very short latencies. *Nature*, **244**, 522–523.
McRae, K., Spivey-Knowlton, M.J., and Tanenhaus, M.K. (1998). Modeling the influence of thematic fit (and other constraints) in on-line sentence comprehension. *Journal of Memory and Language*, **38**, 283–312.
Mehler, J., Bever, T.G., and Carey, P. (1967). What we look at when we read. *Perception and Psychophysics*, **2**, 213–218.
Meseguer, E., Carreiras, M., and Clifton, C., Jr (2002). Overt reanalysis strategies and eye movements during the reading of mild garden path sentences. *Memory and Cognition*, **30**, 551–562.
Miller, G.A. (1962). Some psychological studies of grammar. *American Psychologist*, **17**, 748–762.
Mitchell, D.C. (2004). On-line methods in language processing: Introduction and historical review. In M. Carreiras and C.J. Clifton (eds.) *The on-line study of sentence comprehension: Eyetracking, ERPs, and beyond*. Brighton: Psychology Press.
Mitchell, D.C. and Shen, X. (in press). The timing and control of regressive saccades in reading. *Cognition*.
Mitchell, D.C., Shen, X., Green, M.J., and Hogdson, T.L. (2008). Accounting for regressive eye-movements in models of sentence processing: A reappraisal of the selective reanalysis hypothesis. *Journal of Memory and Language*, **59**, 266–293.
Ni, W., Fodor, J.D., Crain, S., and Shankweiler, D. (1998). Anomaly detection: Eye movement patterns. *Journal of Psycholinguistic Research*, **27**, 515–540.
Pearlmutter, N.J., Garnsey, S.M., and Bock, K. (1999). Agreement processes in sentence comprehension. *Journal of Memory and Language*, **41**, 427–456.
Pearlmutter, N.J. and MacDonald, M.C. (1995). Individual differences and probabilistic constraints in syntactic ambiguity resolution. *Journal of Memory and Language*, **34**, 521–542.
Pickering, M.J. and Traxler, M. (2001). Strategies for processing unbounded dependencies: Lexical information and verb-argument assignment. *Journal of Experimental Psychology: Learning, Memory and Cognition*, **27**, 1401–1411.
Pickering, M. and Traxler, M. (2003). Evidence against the use of subcategorisation frequency in processing unbounded dependencies. *Language and Cognitive Processes*, **18**, 469–503.
Pollatsek, A., Reichle, E., and Rayner, K. (2006). Tests of the E-Z Reader model: Exploring the interface between cognition and eye-movement control. *Cognitive Psychology*, **52**, 1–56.
Rayner, K. and Frazier, L. (1987). Parsing temporarily ambiguous complements. *Quarterly Journal of Experimental Psychology*, **39A**, 657–673.
Rayner, K. and Sereno, S.C. (1994a). Regressive eye movements and sentence parsing: On the use of regression-contingent analyses. *Memory and Cognition*, **22**, 281–285.
Rayner, K. and Sereno, S.C. (1994b). Regression-contingent analyses: A reply to Altmann. *Memory and Cognition*, **22**, 291–292.
Rayner, K., Carlson, M., and Frazier, L. (1983). The interaction of syntax and semantics during sentence processing:Eye movements in the analysis of semantically biased sentences. *Journal of verbal Learning and verbal Behavior*, **22**, 358–374.

49-Liversedge-49.indd 908 4/14/2011 5:23:51 PM

OUP UNCORRECTED PROOF – FIRST-PROOF, 14/04/2011, GLYPH

Rayner, K., Warren, T., Juhasz, B.J., and Liversedge, S.P. (2004). The effect of plausibility on eye movements in reading. *Journal of Experimental Psychology: Learning, Memory and Cognition*, **30**, 1290–1301.

Reichle, E., Warren, T., and McConnell, K. (2009). Using E-Z Reader to model the effects of higer-level language processing on eye movements during reading. *Psychonomic Bulletin and Review*, **16**, 1–21.

Reichle, E.D., Pollatsek, A., Fisher, D.F., and Rayner, K. (1998). Toward a model of eye movement control in reading. *Psychological Review*, **105**(1), 125–156.

Rayner, K., and Well, A.D. (1996). Effects of contextual constraint on eye movements in reading: A further examination. *Psychonomic Bulletin and Review,* **3**, 504–509.

Rayner, K., Ashby, J., Pollatsek, A, and Reichle, E.D. (2004). The effects of frequency and predictability on eye fixations in reading: Implications for the E-Z Reader model. *Journal of Experimental Psychology: Human Perception and Performance*, **30**, 720–732.

Sanford, A. and Sturt, P. (2002). Depth of processing in language comprehension: Not noticing the evidence. *Trends in Cognitive Sciences*, **6**, 382–386.

Sereno, S. and Rayner, K. (2003). Measuring word recognition in reading: Eye movements and event-related potentials. *Trends in Cognitive Sciences*, **7**, 489–493.

Staub, A. (2007). The parser doesn't ignore intransitivity, after all. *Journal of Experimental Psychology: Learning, Memory and Cognition*, **33**, 550–569.

Staub, A. (2010). Eye movements and processing difficulty in object relative clauses. *Cognition,* **116**, 71–86.

Staub, A. (submitted). The lexical predictability effect: Distributional analysis of fixation durations.

Staub, A. and Clifton, C. Jr (2006). Syntactic prediction in language comprehension: Evidence from either . . . or. *Journal of Experimental Psychology: Learning, Memory and Cognition*, **32**, 425–436.

Staub, A. and Rayner, K. (2007). Eye movements and on-line comprehension processes. In G. Gaskell (ed.) *Oxford Handbook of Psycholinguistics* (pp. 327–342). Oxford: Oxford University Press.

Staub, A., Clifton, C., Jr, and Frazier, L. (2006). Heavy NP shift is the parser's last resort: Evidence from eye movements. *Journal of Memory and Language*, **54**, 389–406.

Staub, A., White, S.J., Drieghe, D., Hollway, E.C., and Rayner, K. (2010). Distributional effects of word frequency on eye fixation durations. *Journal of Experimental Psychology: Human Perception and Performance*, **36**, 1280–1293.

Stowe, L. (1986). Parsing wh-constructions: Evidence for on-line gap location. *Language and Cognitive Processes*, **1**, 227–246.

Tabor, W. and Hutchins, S. (2004). Evidence for self-organized sentence processing: Digging-in effects. *Journal of Experimental Psychology: Learning, Memory and Cognition*, **30**, 431–450.

Tanenhaus, M.K., Spivey-Knowlton, M.J., Eberhard, K.M., and Sedivy, J.C. (1995). Integration of visual and linguistic information in spoken language comprehension. *Science*, **268**, 1632–1634.

Tanenhaus, M. (2007). Eye movements and spoken language processing. In R.P.G. v. Gompel and M.H. Fischer and W.S. Murray and R.L.Hill (eds.) *Eye movements: A window on mind and brain* (pp. 444–469). Oxford: Elsevier.

Traxler, M.J. and Pickering, M.J. (1996). Plausibility and the processing of unbounded dependencies: An eye-tracking study. *Journal of Memory and Language*, **35**, 454–475.

Traxler, M., Pickering, M., and Clifton, C., Jr (1998). Adjunct attachment is not a form of lexical ambiguity resolution. *Journal of Memory and Language*, **39**, 558–592.

Trueswell, J.C., Tanenhaus, M.K., and Kello, C. (1993). Verb-specific constraints in sentence processing: Separating effects of lexical preference from garden-paths. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, **19**, 528–553.

Trueswell, J.C., Tanenhaus, M.K., and Garnsey, S.M. (1994). Semantic influences on parsing: Use of thematic role information in syntactic disambiguation. *Journal of Memory and Language*, **33**, 285–318.

Van Gompel, R.P.G., Pickering, M., Pearson, J., and Liversedge, S.P. (2005). Evidence against competition during syntactic ambiguity resolution. *Journal of Memory and Language*, **52**, 284–307.

Vasishth, S., Bruessow, S., Lewis, R.L., and Drenhaus, H. (2008). Processing polarity: How the ungrammatical intrudes on the grammatical. *Cognitive Science*, **32**, 685–712.

Warren, T. and Gibson, E. (2002). The influence of referential processing on sentence complexity. *Cognition*, **85**, 79–112.

Waters, G.S. and Caplan, D. (1996). The capacity theory of sentence comprehension: Critique of Just and Carpenter. *Psychological Review*, **103**, 761–772.

49-Liversedge-49.indd 909 4/14/2011 5:23:51 PM