Oxford Handbooks Online

Direct Lexical and Nonlexical Control of Fixation Duration in Reading 🔓

Eyal M. Reingold, Heather Sheridan, and Erik D. Reichle
The Oxford Handbook of Reading *(Forthcoming)*
Edited by Alexander Pollatsek and Rebecca Treiman

[−] **Abstract and Keywords**

This chapter focuses on the *eye-mind link* in reading, or how perceptual and cognitive processes influence when and where the eyes move when people read. The chapter is organized into four parts. First, early theoretical accounts of the eye-mind link are reviewed, and key findings that are problematic for these accounts are discussed. Timing constraints on the eye-mind link that have been derived from behavioral and neurophysiological studies are examined, along with the implications of these constraints for current models of eye-movement control in reading. Next, evidence is provided for the direct control of eye movements during reading from a number of eye-movement experiments that have used distributional analyses and survival analyses to examine the time course over which perceptual and/or lexical variables affect fixation durations during reading. Finally, the findings of the review are summarized, and possible directions for future research on this topic are presented.

Keywords: eye-mind link, lexical processing, distributional analyses, time course, eye-movement control, fixation duration

The subjective experience reported by skilled readers often includes descriptions of smooth and continuous gliding of gaze position across the line of text. However, 135 years ago Emile Javal (see Huey, 1908) observed that readers' eyes do not sweep smoothly across the text, but instead make a sequence of high velocity eye movements during which vision is largely suppressed (referred to as *saccades*). The periods between saccades during which the eye is relatively still and visual information is encoded are referred to as *fixations*. In order to enable the extraction of fine visual features of the text during reading, saccades align the high-acuity *foveal* region of the visual system (the central 2° of vision) with the portion of the text that is being encoded. This is necessary because visual acuity declines rapidly as the location of the retinal image of the text shifts from the fovea to the surrounding *parafoveal* region (1° to 5° on either side of fixation) and *peripheral* region (beyond 5° on either side of fixation) of the visual field.

More than a century of research employing eye-movement measures and techniques revealed that the subjective experience of effortless skilled reading obscures an intricate orchestration of a wide array of oculomotor, perceptual, lexical, linguistic, and cognitive processes (for reviews, see Rayner, 1998, 2009; and Schotter & Rayner, this volume). Indeed, the rapidly growing use of eyetracking methodology in reading research was motivated in part by the assumption that the record of the locations and durations of fixations is a valid and useful trace measure for inferring the processes underlying reading performance. Consequently, extensive empirical and theoretical efforts have been directed at developing models of eye-movement control during reading. These models attempt to explain the factors that determine *when* the eyes move (i.e., fixation durations) as well as *where* the eyes move (i.e., fixation locations). One source of considerable controversy concerns the influence of cognitive processes on the location and duration of fixations (henceforth, the *eye-mind link*). There is little doubt that, for reading to be efficient, some form of coordination between the progression of the eyes over the text and comprehension processes must occur. This fact was acknowledged even when the behaviorist era in psychology

discouraged any attempt to infer mental processes from eye-movement data. For example, Tinker (1958), perhaps the most prominent eye movement and reading researcher of that era, stated that "in addition to seeing clearly during a fixation pause, the reader must comprehend the ideas and relationships involved. Actually, therefore, pause duration includes perception time plus thinking time" (p. 218). As an illustration of the importance of the eye-mind link to skilled reading, consider the case in which the synchronisation between eye movements and comprehension processes breaks down during *mind-wandering* episodes (sometimes referred to as *mindless reading*). There is now considarable evidence indicating that while the general characteristics of eye movement parameters are similar between normal reading and mindless reading, there are important quantitative and qualitative differences in the observed pattern of eye movements across these conditions (e.g., Reichle, Reineberg, & Schooler, 2010; Schad, Nuthmann, & Engbert, 2012). For example, whereas the durations of fixations during normal reading are modulated by local properties of the text being read (e.g., the frequency of the word being fixated; Inhoff & Rayner, 1986; Just & Carpenter, 1980), this is less true during mindless reading (e.g., word-frequency effects are absent or much attenuated in size; Reichle et al., 2010; Schad et al., 2012).

Given the critical importance of the eye-mind link in reading, our primary goal is to examine the validity of the *direct lexical-control hypothesis* (e.g., Rayner & Pollatsek, 1981), which argues that lexical and linguistic processes play a major role in determining the durations of individual fixations during reading. Recently, Reingold, Reichle, Glaholt, and Sheridan (2012) proposed a general framework for the investigation of the possible mechanisms that might mediate the control of fixation durations in reading. In the present chapter, we present an extended version of this approach. Accordingly, we begin with a brief overview of the central ideas, terminology, and assumptions concerning eye-movement control in reading. Next we outline some of the timing constraints that must be considered in evaluating the feasibility of the direct control of eye movements in reading and their implications for models of eye-movement control in reading. Finally, we review several categories of empirical findings that make a compelling case for a tight link between visual and lexical processing and fixation duration in reading. It is important to note that in the present chapter we exclusively review evidence from reading studies that employed European alphabetic languages.

Eye-Movement Control in Reading: Brief History and Basic Concepts

Models of eye-movement control in reading attempt to explain the considerable variability in both saccade amplitude (Mean = 7-9 letter spaces; Range = 1-20 letter spaces) and fixation duration (Mean = 200–250 ms; Range = 50-1,000 ms). Prior to the 1970s, there was a great deal of skepticism over whether cognitive processes could have an impact on eye movements (for reviews see Rayner, 1978; Rayner & McConkie, 1976). This was in part based on the *cognitive-lag assumption*, or the widely held belief that cognition was simply too slow to have an impact on eye-movement parameters (e.g., Kolers, 1976). For that reason, it was commonly believed that skilled reading was characterized by a consistent and nonvariable pattern of forward eye movements, with the exception of occasional *regressions*, or backward eye movements to previously read text. These early conceptualizations of eye-movement control in reading (called *minimal-control models* by Rayner, 1978) ascribed variability in saccade amplitude and fixation duration to random variation or physiological factors and postulated no meaningful association between eye movements and properties of the fixated text.

Minimal-control models were unable to explain the finding that difficult text passages produced longer fixation durations and shorter saccade amplitudes. This led to the development of *indirect-control models*, which assumed that cognition can have delayed (i.e., non-real-time) influences on fixation durations and saccade amplitudes based on global processing difficulty and contextual factors (e.g., task instructions). For example, *gain-control models* (e.g., Kolers, 1976) assumed that fixation duration and saccade amplitude varied randomly around a preset rate that (on average) allowed enough time to encode the text, but with cognition being used to adjust the overall reading rate via feedback to the oculomotor system. Similarly, buffer-control models (e.g., Bouma & DeVoogd, 1974) assumed that readers maintain an optimal reading rate by increasing the speed of their eye movements whenever their cognitive buffer is empty and decreasing the speed whenever the buffer is full. Thus, indirect-control models could account for effects of text difficulty in a manner that does not require assuming immediate cognitive influences.
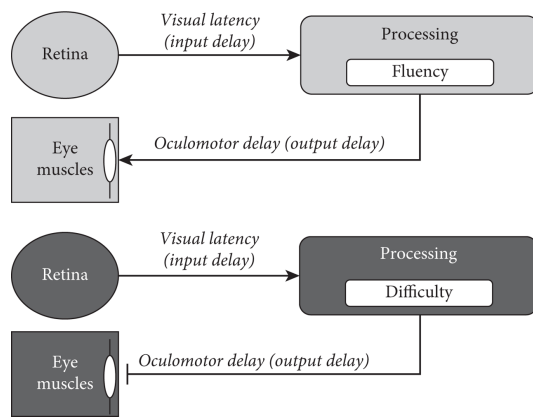
Interestingly, however, more than fifty years prior to the introduction of indirect-control models, Buswell (1922) reported a finding that could not be explained by these models. Specifically, Buswell observed that fixation

durations on unfamiliar words were longer than fixations on other words, and given that indirect-control models assume that the properties of the fixated word could have no bearing on the duration of that fixation, such models could not account for this particular finding. Although the theoretical significance of this finding might have been underappreciated at the time, it latter spurred the development of another class of eye-movement control models—those that posit direct control. In marked contrast to indirect-control models which assume *delayed* adjustment of fixation duration based on the *global* processing difficulty of the text, *direct-control models* argue for an *immediate* fixation-by-fixation adjustment based on the properties of the *local* stimulus (i.e., the word being fixated). Thus in the context of the eye-movement control literature, the direct/indirect dichotomy often incorporates both the immediate/delayed and local/global distinctions. For example, in the *Reader* model proposed by Just and Carpenter (1980) two key assumptions were incorporated: (1) the *immediacy assumption* which hypothesized that readers will attempt to interpret each word as soon it is encountered, even though the initial interpretation might occasionally turn out to be wrong in light of subsequent visual, lexical, semantic, or syntactic processing, and (2) the *eye-mind assumption* which postulated that the currently fixated word is processed completely before the eyes move to the next word. Thus, according to this model, eye-movement control entails both immediate and local control (i.e., the fixation duration on a word exclusively reflects the processing of that word).

Unfortunately, there is considerable vagueness and inconsistency in the literature concerning the use of the terms "immediate" and "local" as part of the definition of direct-control. For example, it is often unclear if immediate processing of the fixated word (Word *N*) implies that such processing begins with the first fixation on Word *N*. This simple view is not tenable, because it has long been known (see Rayner, 1978) that information about Word *N* can be extracted during a fixation on the previous word (i.e., the *parafoveal preview* of Word *N* during the fixation on Word *N-1*). This suggests that the concept of immediacy should be extended to include the preprocessing of Word *N* during the parafoveal preview. Similarly, it is often unclear if local control implies control based entirely on the processing of Word *N*, or whether it should be extended to include the processing of the adjacent words (e.g., Word *N-1* and Word *N+1*). To avoid the ambiguities inherent in the terms "immediate" and "local," Reingold et al. (2012) defined "direct control" as the assumption that the processing of the properties of the fixated word (Word *N*) influences the timing of the saccade terminating that fixation, regardless of whether this processing was initiated while Word *N* was foveated or when it was parafoveally processed during fixations on the previous word (Word *N-1*).

Early direct-control models made vastly different assumptions concerning the role of ongoing lexical and linguistic processes in controlling eye movements in reading (see Rayner, 1998, 2009 for reviews). *Oculomotor* models (e.g., McConkie, Kerr, Reddix & Zola, 1988; McConkie, Kerr, Reddix, Zola & Jacobs, 1989; O'Regan, 1990) assumed that nonlexical, low-level information determines eye-movement control in reading. In contrast, *processing* models (e.g., Just & Carpenter, 1980; Henderson & Ferreira, 1990; Morrison, 1984; Pollatsek & Rayner, 1990; Rayner & Pollatsek, 1981, 1989) advocated a critical role for lexical and attentional processes. The nature of this debate has become more complex in recent years with several mixed-control models that incorporate combinations of direct and indirect control mechanisms. To help clarify these issues, Reingold et al. (2012) proposed a taxonomy of eye-movement control mechanisms based on two orthogonal dimensions: (1) the type of eye-movement control that is assumed (direct vs. indirect) and (2) the type of information (lexical vs. nonlexical) used in the control. Reingold et al. further proposed two nonmutually exclusive general types of direct-control mechanisms: (1) a *triggering mechanism* whereby some index of Word *N* processing fluency triggers the programming of the saccade terminating a fixation, and (2) an *interference mechanism* whereby some index of Word *N* processing difficulty delays the initiation and/or execution of the saccade terminating a fixation (see Figure 1). Based on the preceding taxonomy, the assumption that the completion of some stage of lexical processing initiates saccadic programming (e.g., Reichle, Pollatsek, Fisher, & Rayner, 1998) is an example of a direct-control triggering mechanism based on lexical information. In contrast, the proposal that lexical processing difficulty inhibits saccade initiation (e.g., Engbert, Nuthmann, Richter, & Kliegl, 2005) represents a direct-control interference mechanism based on lexical information. Examples of direct-control mechanisms based on the processing of prelexical visual information also include both triggering (e.g., McDonald, Carpenter, & Shillcock, 2005) and interference versions (e.g., Reilly & Radach, 2006). Furthermore, examples of indirect lexical mechanisms include a cognitive-buffer assumption (e.g., Bouma & DeVoogd, 1974) and the assumption that saccades are initiated at an average rate that is occasionally adjusted to support the overall pace of lexical processing (e.g., Kolers, 1976). Conversely, saccade triggering by a random timer (e.g., Engbert et al., 2005) constitutes an example of an indirect
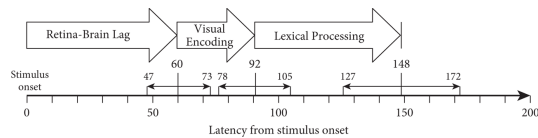
nonlexical control mechanism.

Figure 1 A schematic diagram showing two general types of direct-control mechanisms: A triggering mechanism whereby some index of the fluency of processing of the fixated word triggers the programming of the saccade terminating the fixation (top panel), and an interference mechanism whereby some index of the difficulty of processing of the fixated word produces delays in the initiation or execution of the saccade terminating the fixation (bottom panel). In either triggering or interference mechanisms, the first discernible influence of the processing of the fixated word on the timing of the saccade terminating that fixation would be expected to be constrained by the minimum input (visual), output (oculomotor), and processing delays.

It is important to emphasize that the taxonomy proposed by Reingold et al. (2012) provides a basis for classifying the mechanisms that control eye movements during reading, and *not* the models themselves, which often incorporate more than a single mechanism. Interestingly, most current models of eye-movement control propose either triggering or interference mechanisms but not both (but see Reingold et al., 2012). Another curious of aspect of current models is the fact that they largely ignore (but see Ehrlich & Rayner, 1983; Kennedy, 1998; Kennedy, Pynte & Ducrot, 2002; Reingold et al., 2012; Risse & Kliegl, 2012) an important distinction made by Rayner and McConkie (1976) between eye-movement control that is driven by the output of various processes versus eye-movement control that is based on a system that monitors the progress of such processes (henceforth called the *process-monitoring hypothesis*). In the final section of this paper we briefly discuss the potential advantage of incorporating process monitoring into current models of eye-movement control in reading. Thus over the past four decades, an intensive investigation of the nature of eye-movement control during reading has generated a wealth of findings as well as considerable controversy. Recently, the theoretical focus in this field has shifted away from qualitative models and toward quantitative implemented models (e.g., Engbert et al., 2005; McDonald et al., 2005; Reichle et al., 1998; Reilly & Radach, 2006; Salvucci, 2001). Importantly, these models require precise (quantitative) architectures that specify the mechanisms that control the eyes during reading, which then raises questions about whether the theoretical assumptions and parameters that are incorporated into the models are feasible given the available evidence about neural delays in the perceptual and oculomotor systems. These timing constraints are explored in the next section.

Timing Constraints and Models of Direct Control in Reading

To be plausible, the direct control of fixation duration in reading must respect fairly severe timing constraints. As shown in Figure 1, for either triggering or interference mechanisms the fastest influence of the processing of the properties of Word *N* on the timing of the saccade terminating a fixation on Word *N* should equal the sum of the duration of the following intervals: (1) *minimum input delay*, or the time required for information about Word *N* to reach the cortical systems where processing of Word *N* begins; (2) *processing delay*, or the time required for the processing system (e.g., visual, lexical) or the process-monitoring system to establish that the encoding of Word *N* is progressing well (i.e., processing fluency) or that progress is stalled (i.e., processing difficulty); and (3) *minimum output delay*, or the time required to transmit a facilitatory (triggering) or inhibitory (interference) signal to the oculomotor system and brainstem circuitry that is ultimately responsible for moving the eyes. In this section we briefly summarize what has been learned about direct-control timing constraints from studies using two different electophysiological measures—*event-related potentials* (*ERP*s) and *megnetoencephalography* (*MEG*).

Click to view larger

Figure 2 A schematic diagram, based on Reichle and Reingold's (2013) review of studies employing ERP and MEG methodology, displaying mean and range estimates of input latencies involved in the arrival of text information to cortical processing centers (retina-brain lag), visual encoding, and lexical processing.

Reichle and Reingold (2013) reviewed studies using ERP and MEG methodology in order to evaluate the minimum latencies with which visual information can be propagated from the eyes to the brain (i.e., the *retina-brain lag*), and the processing delays associated with visual encoding and lexical processing of printed words. As explained earlier, several models of eye-movement control in reading posit a tight link between the eye and mind, with lexical processing directly triggering most decisions about when to start programming a saccade to move the eyes from one word to the next. One potential problem with this theoretical assumption, however, is that it may violate neurophysiological constraints imposed by the time required to first encode visual information, then complete some amount of lexical processing, and then program a saccade. Note that this objection is simply a restatement of the cognitive-lag hypothesis that was discussed earlier. The findings from the studies reviewed by Reichle and Reingold (2013) are summarized in Figure 2. Given that the estimates derived from these studies are inherently conservative because they correspond to the first statistically reliable effects of experimental variables on neuroimaging markers, Figure 2 displays the minimum, mean, and maximum values of each estimate. As can be seen by an inspection of this figure, mean estimates of 60, 92, and 148 ms were obtained for the retina-brain lag, visual encoding time, and lexical processing time, respectively.

If one accepts that the latency for lexical processing is approximately 150 ms, then the remaining time in the average fixation duration of 200 to 250 ms (i.e., 50–100 ms) is insufficient for completing all of the operations that are necessary for initiating and programming the saccade that terminates the fixation. This is because eye-movement experiments (e.g., Becker & Jürgens, 1979; Rayner, Slowiaczek, Clifton & Bertera, 1983) suggest that saccades require 120 to 200 ms to program. Furthermore, Reingold et al. (2012) found that word-frequency effects (a marker of lexical processing) on target words were discernible more than 100 ms earlier when target words were available for parafoveal processing (i.e., normal reading) than when parafoveal processing was prevented. Consideration of these findings led Reichle and Reingold (2013) to argue that, given that the average fixation duration on Word *N* lasts approximately 250 ms, the temporal constraints imposed by visual processing and saccadic programming are too severe to permit direct lexical control of fixation duration without a significant amount of parafoveal processing (i.e., preprocessing of Word *N* from Word *N*-1).

The preceding estimates derived from ERP and MEG studies have broader implications for direct-control models that incorporate a triggering mechanism. Most importantly, these estimates underscore the fact that triggering must be based on shallow, partial, and rapid processing of Word *N*. This insight is consistent with the trend in the literature. Recall that the Reader model proposed by Just and Carpenter (1980) postulated a triggering mechanism based on the complete lexical and postlexical processing of Word *N*. More recently, advocates of the triggering mechanism have adopted a much more modest view about how much word processing must be completed to trigger an eye movement. For example, in the EMMA model (Salvucci, 2001), the saccadic program to move the eyes from Word *N* to Word *N+1* is triggered by the encoding of Word N, but not its subsequent processing. Similarly, the E-Z Reader model (Reichle, et al., 1998; see also Reichle & Sheridan, this volume) assumes that a superficial stage of lexical processing triggers saccadic programming. This early stage of processing has been described as corresponding to either a rapid recognition response that reflects the familiarity of Word N (Reichle & Perfetti, 2003) or orthographic processing (Reichle, Tokowicz, Liu, & Perfetti, 2011). By either interpretation the completion of this stage indicates that access to the meaning of Word *N* is imminent, so that the oculomotor system can begin programming a saccade to move the eyes to Word *N+1* (see also Reingold & Rayner, 2006; Sheridan & Reingold, 2013). The amount of cognitive processing that, by assumption, is necessary to initiate saccadic programming is even further reduced in the *SERIF* (McDonald et al., 2005) and *Glenmore* (Reilly & Radach, 2006) models, where visual word encoding rather than lexical processing provides the trigger that determines when the eyes will move.

Finally, it is important to examine the temporal constraints that are relevant for direct-control models which

incorporate an interference mechanism. Although there were several proposals of interference mechanisms in the literature on eye-movement control in reading (e.g., Engbert et al., 2005; Nuthmann & Henderson, 2012; Reingold et al., 2012; Yang & McConkie, 2001), the most complete instantiation of such a mechanism is incorporated into the *SWIFT* model (e.g., Engbert et al., 2005). According to this model, saccades are triggered by an autonomous random timer (which is an exemplar of an indirect-control mechanism), and not by the completion of some cognitive process. Importantly, lexical processing difficulty can modulate fixation durations by actively inhibiting the timer so that it cannot initiate new saccadic programs. The assumption here is that by preventing the initiation of saccadic programming, fixations will be lengthened, allowing additional time for lexical processing. In order to avoid unnecessary interruptions to the reading process, it is likely that establishing processing difficulty would require a more conservative threshold and longer delay than establishing processing fluency. However, experiments using the *saccadic inhibition paradigm* in reading (e.g., Reingold & Stampe, 1999, 2000, 2002, 2003, 2004) suggest that once processing difficulty has been established, the minimum latency for inhibiting saccades via a direct-control interference mechanism should be on the order of 20 to 30 ms (see Reingold & Stampe, 2000, 2002 for reviews of the timing constraints involved in saccadic inhibition based on evidence from both behavioral and neurophysiological studies). In addition, temporal constraints are further relaxed for a reading model such as *SWIFT* due to the assumption that multiple words are processed in parallel, thereby permitting the parafoveal processing of Word *N* during fixations on Word *N-1* and Word *N-2*.

The Empirical Case for Direct Control

It is now generally accepted that fixation times in reading are influenced by both lexical and nonlexical variables. Importantly, only the analysis of the duration of the very first fixation on Word *N* (henceforth, *first-fixation duration*) offers a straightforward opportunity for examining the possible influence of direct control of fixation duration (see Reingold, Yang, & Rayner, 2010 for a related discussion). This is because refixations on the word, either immediate (i.e., on *the first-pass* through the text) or delayed (i.e., rereading the word following a *regression* back to that region of text), might be influenced by a variety of other factors such as the memory for the previous foveal analysis. Nonlexical variables with an influence on first-fixation duration include word length (e.g., Just & Carpenter, 1980; Rayner, Sereno & Raney, 1996) and initial landing position (e.g., Kliegl, Nuthmann, & Engbert, 2006; McDonald et al., 2005; Nuthmann, Engbert, & Kliegl, 2005, 2007; Vitu et al., 2001, 2007). In addition, lexical variables which were demonstrated to influence first-fixation duration in reading include word frequency (Inhoff & Rayner, 1986; Rayner & Duffy, 1986; Reingold et al., 2012; see White, 2008 for a review), contextual constraint or predictability (Ehrlich & Rayner, 1981; Rayner, Ashby, Pollatsek, & Reichle, 2004; Rayner & Well, 1996; Sheridan & Reingold, 2012a), lexical ambiguity (e.g., Duffy, Morris, & Rayner, 1988; Rayner & Duffy, 1986; Sheridan & Reingold, 2012b; Sheridan, Reingold, & Daneman, 2009; see Duffy, Kambe, & Rayner, 2001 for a review), and age of acquisition (e.g., Juhasz & Rayner, 2006). However, simply showing that a variable affects the mean first-fixation duration is insufficient for demonstrating direct control because such an effect might be due to a very infrequent but sizable influence of a variable that does not have an impact on the vast majority of fixations.

The analysis of distributions is inherently more suitable than the analysis of mean fixation durations for determining the time-course of the influence of variables on fixation duration. Accordingly, in this section of the chapter we primarily focus on reviewing the results from recent studies that employed distributional analysis methods in order to study the time course of direct control of fixation duration in reading. Specifically, we summarize findings from studies using an ex-Gaussian fitting procedure that was introduced by Staub, White, Drieghe, Hollway, and Rayner (2010), and a survival analysis technique that was introduced by Reingold et al. (2012). In addition, we explore how these findings provide convergent evidence for the conclusions from earlier investigations which employed the *text-onset delay* paradigm (e.g., Dambacher, Slattery, Yang, Kliegl & Rayner, 2013; Hohenstein, Laubrock & Kliegl, 2010; Inhoff, Eiter & Radach, 2005; Luke et al., 2013; Morrison, 1984; Nuthmann & Henderson, 2012; Rayner & Pollatsek, 1981) and the *disappearing text* paradigm (Blythe, Liversedge, Joseph, White, & Rayner, 2009; Ishida & Ikeda, 1989; Liversedge, Rayner, White, Vergilino-Perez, Findlay & Kentridge 2004; Rayner, Inhoff, Morrison, Slowiaczek, & Bertera, 1981; Rayner, Liversedge, & White, 2006; Rayner, Liversedge, White, & Vergilino-Perez, 2003; Rayner, Yang, Castelhano, & Liversedge, 2011).

Direct Control and Evidence from Distributional Analysis Methods

Recently, ex-Gaussian fitting (Staub et al., 2010) and a survival analysis technique (Reingold et al., 2012) were

used to provide valuable information about the time-course of lexical and nonlexical influences on fixation durations during reading. The characteristic shape of the empirical distribution of fixation durations resembles a Gaussian normal distribution, but the right tail of the distribution is typically skewed to some degree. Consequently, the ex-Gaussian distribution, which is the convolution of the Gaussian normal distribution and an exponential distribution, appears to be a good candidate for modeling the empirical distributions of fixation durations. The ex-Gaussian distribution was previously established to generate excellent fits for reaction time distributions (see Balota & Yap, 2011 for a review) and Staub et al. (2010) first demonstrated its great promise for modeling fixation durations in reading. The ex-Gaussian distribution can be specified with the parameters μ (which corresponds to the mean of the Gaussian distribution), σ (which corresponds to the standard deviation of the Gaussian distribution), and τ (the exponential component which indicates the degree of skew). Importantly, the sum of the μ and τ parameters from the ex-Gaussian distribution equals the mean of the empirically obtained fixation-duration distribution, and a comparison of the best-fitting μ and τ parameters can reveal whether a variable's impact on the mean empirical fixation durations is due to an overall shift in the location of the distribution and/or a change in the degree of skew. Whereas a shift effect (i.e., a difference in μ between conditions) indicates that the variable has an early acting influence on the majority of fixation durations, a skew effect (i.e., a difference in τ between conditions) indicates that the variable primarily influences the long fixation durations.

Using this logic, Staub et al. (2010) fitted an ex-Gaussian distribution to individual participants' first-fixation duration distributions on both high- and low-frequency target words. These fits indicated that the low-frequency distribution was significantly shifted to the right of the high-frequency distribution, and that the low-frequency distribution also exhibited greater positive skew than the high-frequency distribution. The finding that word frequency caused a shift in the distributions indicates that this lexical variable has an impact on both short and long fixations (see Rayner, 1995); this was predicted by the direct lexical-control hypothesis. However, the more pronounced positive skew for the low-frequency distribution also indicates that long fixations are differentially affected by word frequency.
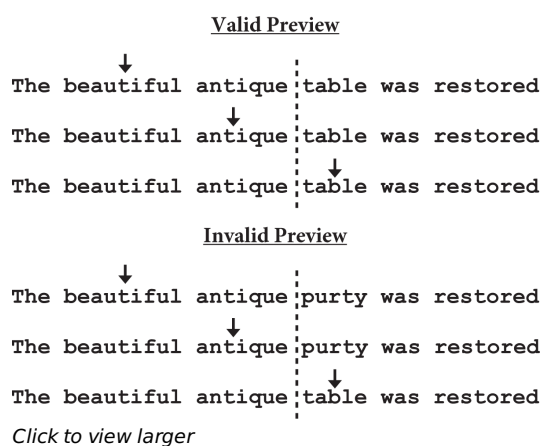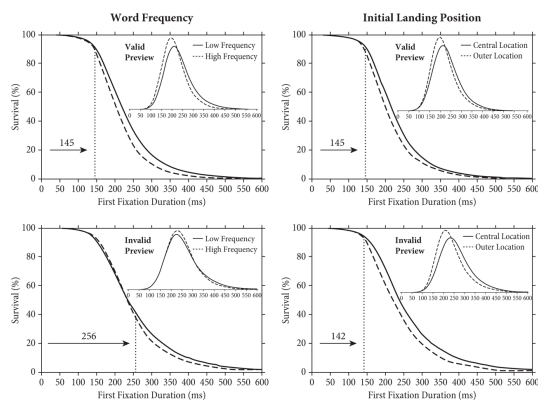
Valid Preview

↓
The beautiful antique ¦table was restored

↓
The beautiful antique ¦table was restored

↓
The beautiful antique ¦table was restored

Invalid Preview

↓
The beautiful antique ¦purty was restored

↓
The beautiful antique ¦purty was restored

↓
The beautiful antique ¦table was restored

Click to view larger

Figure 3 An illustration of the valid and invalid preview conditions that were used by Reingold et al. (2012). Three consecutive fixations are shown in each condition (the arrow above each sentence denotes the location of the fixation). In invalid preview trials, an unrelated letter string (e.g., purty) occupied the position of the target word (e.g., table). During the saccade that crossed an invisible boundary (illustrated by the dotted vertical line) the target word replaced the unrelated letter string. In contrast, in the valid preview condition which represents normal reading, target words were always displayed throughout the trial.

Another approach for examining the distributions of fixation duration was introduced by Reingold et al. (2012). This approach was aimed at deriving a precise estimate for the first discernible influence of a variable on fixation duration. Specifically, Reingold et al. (2012) explored the onset of the influence of a lexical variable (word frequency: high vs. low frequency) and a nonlexical variable (initial landing position on the fixated word: central vs. outer location) on first-fixation duration using a novel survival analysis technique. In this procedure, for a given time *t*, the percentage of first fixations with a duration greater than *t* is referred to as the percent *survival* at time *t*. Thus, when *t* equals zero survival is at 100%, but then declines as *t* increases. For each variable and condition, Reingold et al. (2012) calculated survival curves and computed confidence intervals using a bootstrap resampling procedure (Efron & Tibshirani, 1994) in order to examine the earliest point at which the survival curves for high- versus low-frequency words and for central- versus outer-location fixations first started to diverge (henceforth referred to as the *divergence point*). Importantly, Reingold et al. (2012) argued that these divergence points

provide estimates of the earliest significant influence of word frequency and initial landing position on first-fixation duration, and consequently that this analysis technique is uniquely suited for testing the feasibility of lexical and nonlexical direct-control mechanisms.

In addition, in order to test the role of parafoveal processing in enabling direct control of first-fixation duration, Reingold et al. (2012) employed the *gaze-contingent boundary paradigm* (Rayner, 1975) to contrast invalid and valid preview trials. As shown in Figure 3, in invalid preview trials an unrelated letter string occupied the position of the target word and was replaced with the target word during the saccade that crossed an invisible boundary located just to the left of that word. In contrast, in the valid preview condition which represents normal reading, target words were always displayed throughout the trial. Finally, in order to replicate and extend the findings reported by Staub et al. (2010), in addition to survival analysis, Reingold et al. (2012) also used ex-Gaussian fitting in order to investigate the time-course of the influence of word frequency and initial landing position in both the valid and invalid preview conditions.

Click to view larger

Figure 4 Key findings reported by Reingold et al. (2012) based on the survival analysis of first-fixation durations for both valid preview (top panels) and invalid preview (bottom panels), as a function of word frequency (left panels) or initial landing position (right panels). In each panel, the divergence point is marked by a vertical dashed line and the ex-Gaussian density functions are shown in the top right section of the panel (see text for details).

Figure 4 displays some of the key findings reported by Reingold et al. (2012). As can be seen by an inspection of the divergence points shown in the figure, under normal reading conditions (i.e., the valid preview condition shown in the top two panels), word frequency and initial landing position produced an equally rapid influence on first-fixation duration (divergence point = 145 ms). In contrast, preventing parafoveal processing of target words (i.e., the invalid preview condition shown in the bottom two panels) had a dramatic impact on the onset of the word-frequency effect (divergence point = 256 ms), but did not influence the timing of the effect of the initial landing position (divergence point = 142 ms). Similarly, the results of the ex-Gaussian analysis indicated a strong effect of preview validity on word frequency. In the valid preview condition, the low-frequency distribution exhibited a rightward shift (i.e., μ effect) and a greater skew (i.e., τ effect), whereas in the invalid preview condition only a τ effect was obtained. Furthermore, the pattern of results for the initial fixation position was qualitatively different, with a μ effect but not a τ effect occurring in both the valid and invalid preview conditions. Reingold et al. (2012) argued that taken together, these findings clearly demonstrated the critical role of parafoveal processing in enabling direct lexical control of fixation duration despite the tight constraints imposed by neural delays in the perceptual and oculomotor system. In addition, Reingold et al. (2012) suggested that the results from the distributional analyses of the influence of initial landing position on fixation duration provide strong support for the existence of a direct nonlexical control mechanism. Such a mechanism might involve the processing of visual cues that are extracted very early during the first fixation on the word (e.g., Vitu et al., 2001, 2007), or reliance upon the internal monitoring of the signal sent to the oculomotor muscles (i.e., the efference copy) prior to the execution of the saccade that first moved the eyes to the word (Nuthmann et al., 2005, 2007; see also Engbert et al., 2005; McDonald et al., 2005; Reichle, Warren & McConnell, 2009).

Table 1 Summary of the results from studies using ex-Gaussian modeling and/or survival analysis.						
Variable	**Article**	**Fixation**	**Mu**	**Sigma**	**Tau**	**Divergence**

	Reference	Duration	(μ)	(σ)	(τ)	Point
Word Frequency (Low—High Frequency)	Staub et al. (2010)—Exp.1	25**	16**	8[†]	10[†]	---
	Staub et al. (2010)—Exp. 2	27**	13	4	15	---
	Reingold et al. (2012)—Valid Preview	20**	9*	2	11*	145 (9%)
	Reingold et al. (2012)—Invalid Preview	9*	- 8	- 2	16**	256 (60%)
	Sheridan et al. (2013)—Exp.1A, Normal	20**	7*	3	13**	112 (5%)
	Sheridan et al. (2013)—Exp.1A, Unsegmented	20**	7	4	13**	152 (9%)
	Sheridan et al. (2013)—Exp.1B, Normal	19**	9*	4	9*	146 (10%)
	Sheridan et al. (2013)—Exp.1B, Unsegmented	20**	7	6*	12**	169 (15%)
Predictability (Low—High Predictability)	Staub (2011)	16**	14**	5	3	---
	Sheridan & Reingold (2012a)	8*	8	- 1	1	140 (10%)
Lexical Ambiguity (Subordinate—Dominant context)	Sheridan & Reingold (2012b)	12**	8*	0	5	139 (8%)
Preview effect (Invalid—Valid)	Reingold et al. (2012) High Frequency	37**	24**	6	13	133 (5%)
	Reingold et al. (2012) Low Frequency	25**	10	3	14*	172 (20%)
Initial Landing Position (Central—Outer Location)	Reingold et al. (2012) High Frequency	19**	14**	5	3	141 (8%)

	Reingold et al. (2012) Low Frequency	26**	21**	12**	4	144 (8%)
	Reingold et al. (2012) Valid Preview	14**	11**	6*	2	145 (10%)
	Reingold et al. (2012) Invalid Preview	25**	20**	8	2	142 (6%)
Stimulus Quality (Degraded-Normal)	White & Staub (2012)	20**	19**	4	1	---
	White & Staub (2012)	52**	47**	24**	3	---
	Glaholt et al. (2014)	50**	32**	17**	18*	141 (10%)

Note: For the contrasts shown above,

([†]) p < .1,

([*]) p < .05,

([**]) p < .01,

([***]) p < .001.

All divergence points were significant (*p* < .001), and the percentages of fixations with a duration that is shorter than the divergence point are shown in brackets next to each divergence point. Exp. = Experiment. See original studies for details.

As summarized in Table 1, following Staub et al. (2010) and Reingold et al. (2012), the influence of a variety of lexical and nonlexical variables on first-fixation duration have been examined using ex-Gaussian fitting or survival analysis. During normal reading, all of the variables that have been examined to date have shown rapid influences on first-fixation durations, as indicated by a significant μ effect (i.e., a shift effect) for all of the variables in the table, and by survival analysis results showing that the first discernible influence of these variables occurs 112 to 146 ms after fixation onset. Taken together, the ex-Gaussian and survival analysis results provide strong support for direct control by demonstrating that a variety of variables can have a rapid influence on both short and long fixation durations.

The survival analysis technique can also be used to compare the time-course of variables under different reading conditions. As previously discussed, Reingold et al. (2012) showed that word frequency effects were substantially delayed in the absence of a parafoveal preview. Similarly, Sheridan, Rayner, and Reingold (2013) investigated the hypothesis that lexical processing would be delayed by the removal of interword spaces (see Rayner, Fischer, & Pollatsek, 1998). To do this, Sheridan et al. conducted an experiment in which high- and low-frequency words were embedded either in normal (English) text or unsegmented text in which the blank spaces between the words were replaced with random numbers. Sheridan et al. demonstrated that word frequency divergence points were delayed (by 23–40 ms) in the unsegmented condition relative to the normal reading condition. Taken together, these

findings indicate that rapid lexical processing is facilitated by the availability of parafoveal preview and by interword spacing, and these findings demonstrate the usefulness of the survival analysis technique for testing predictions about the time-course of lexical processing (see also Inhoff & Radach, 2014; Schad, Risse, Slattery, & Rayner, 2014).

In addition to considering μ effects and survival divergence points, it is also informative to consider the relationship between the μ and τ parameters shown in Table 1. For example, Staub and Benatar (2013) suggested that τ effects might reflect the probability of processing disruption (i.e., episodes when normal processing fails and some type of repair or recovery process is necessary), whereas μ effects might reflect variations in processing difficulty. For example, the word frequency variable might cause a μ effect because low-frequency words are more difficult to process, and might cause a τ effect because low-frequency words are more likely to produce episodes of processing disruption (e.g., failure to access or integrate a word's meaning). In support of the hypothesis that μ and τ effects for fixation-duration distributions reflect functionally distinct processes, Staub and Benatar (2013) performed a correlation analysis and demonstrated that the μ and τ parameters varied independently across subjects. Moreover, as shown in Table 1, the two parameters appear to be functionally dissociable because it is possible to find instances in which μ effects occur in the absence of τ effects and vice versa. For example, whereas word frequency produced a τ effect in the absence of a μ effect in the invalid preview condition (Reingold et al., 2012), a variety of other variables produced μ effects in the absence of a τ effect, including the initial fixation position (Reingold et al., 2012), predictability (Sheridan & Reingold, 2012a; Staub, 2011), lexical ambiguity (Sheridan & Reingold, 2012b), and stimulus quality (White & Staub, 2012). Furthermore, word frequency produced μ and τ effects during normal reading, as did the contrast between valid and invalid parafoveal preview (Reingold et al., 2012).

Thus, to summarize, Table 1 lists a wide range of ex-Gaussian results, including simultaneous μ and τ effects, selective μ effects, and a selective τ effect. As discussed by Staub and Benatar (2013), the suggestion that μ and τ reflect functionally distinct processes has been controversial (for further discussion of this issue in the reaction-time literature see Matzke & Wagenmakers, 2009), and future work is required to further explore this issue. However, the evidence provided by this method in combination with the evidence of rapid survival divergence points provides support for both lexical and nonlexical direct control by demonstrating a fast-acting influence of several important reading-related variables on fixation durations.

Direct Control and the Text-Onset Delay and Disappearing Text Paradigms

The findings from studies employing distributional analyses methods are also consistent with evidence in support of lexical and nonlexical direct control that was previously obtained using two gaze-contingent techniques, the text-onset delay paradigm (e.g., Dambacher et al., 2013; Hohenstein et al., 2010; Inhoff et al., 2005; Luke et al., 2013; Morrison, 1984; Nuthmann & Henderson, 2012; Rayner & Pollatsek, 1981) and the disappearing text paradigm (Blythe et al., 2009; Ishida & Ikeda, 1989; Liversedge et al., 2004; Rayner et al., 1981; Rayner et al., 2003, 2006, 2011). In this section we briefly outline the key findings from these investigations.
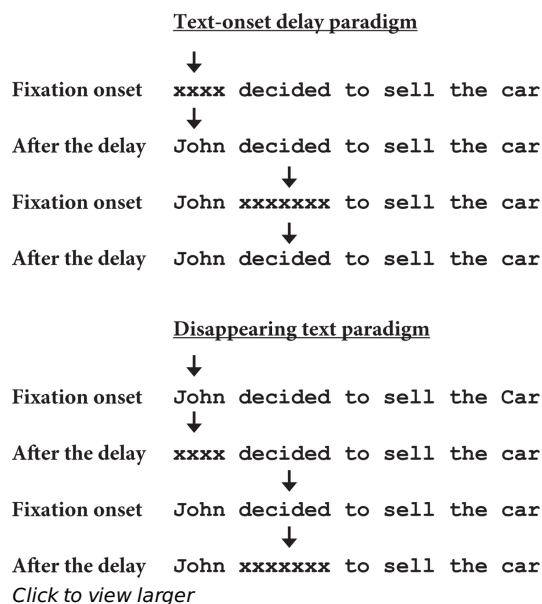
Text-onset delay paradigm

```
                    ↓
Fixation onset    xxxx decided to sell the car
                    ↓
After the delay   John decided to sell the car
                         ↓
Fixation onset    John xxxxxxx to sell the car
                         ↓
After the delay   John decided to sell the car
```

Disappearing text paradigm

```
                    ↓
Fixation onset    John decided to sell the Car
                    ↓
After the delay   xxxx decided to sell the car
                         ↓
Fixation onset    John decided to sell the car
                         ↓
After the delay   John xxxxxxx to sell the car
```

Click to view larger

Figure 5 An illustration of the text-onset delay paradigm and disappearing text paradigm. The arrow above each sentence denotes the location of the fixation. A display change occurs in both paradigms following a certain interval from the onset of each fixation. In the text-onset delay paradigm, a mask which is shown at the onset of the fixation is replaced by the fixated word after a delay. In contrast, in the disappearing text paradigm, the fixated word that is displayed normally at the onset of the fixation is replaced by a mask or blanked after a delay (see text for details).

It is often argued that the text-onset delay paradigm offers the most straightforward approach for demonstrating that information extracted during a fixation has an impact on the timing of the saccade terminating that fixation (i.e., direct control of fixation duration). As illustrated in Figure 5, the basic procedure used in this paradigm involves delaying the availability of a portion of the text during an interval at beginning of each fixation. This "dead time" at the beginning of each fixation is implemented by replacing the text with a visual mask during the preceding saccade and reinstating the text at a certain delay from the onset of the fixation (the range of delays used across studies was 0–350 ms).

Importantly, direct-control models would predict that the saccade terminating the fixation should be delayed and that the magnitude of this delay should be proportional to length of the interval during which the text information was unavailable. In contrast, indirect-control models assume that the properties of the fixated word do not have an impact on the duration of the fixation and consequently would predict no difference in fixation times as a function of the length of the delay. The key findings that were initially reported by Rayner and Pollatsek (1981) and Morrison (1984) provided support for both direct and indirect influences on fixation duration (i.e., mixed-control). Specifically, the general pattern of an increase in fixation duration that was proportional to the length of the delay provided support for the existence of a direct-control mechanism, which influenced a large population of fixations. However, there was a distinct population of fixations with durations that were shorter than the delay (especially for longer text-onset delays). These fixations, which were terminated prior to the removal of the mask, likely reflected the influence of an indirect-control mechanism and/or saccadic programming that was initiated based on parafoveal processing of the text during the previous fixation (see Dambacher et al., 2013; Hohenstein et al., 2010; Inhoff et al., 2005 for investigations of the role of parafoveal processing using the text-onset delay paradigm). One potential complication in interpreting the findings obtained using the text-onset delay paradigm is due to the fact that the visible display change due to the removal of the mask results in saccadic inhibition (e.g., Reingold & Stampe, 1999, 2000, 2002, 2003, 2004). However, although saccadic inhibition clearly contributes to prolonging fixation duration, it could not fully account for the qualitative pattern of findings that is observed across delays (see also Luke, Nuthmann, & Henderson, 2013; Nuthmann & Henderson, 2012; Slattery, Angele, & Rayner, 2011), and consequently it is safe to conclude that the results from studies employing the text-onset delay paradigm provide strong support for a sizable influence of direct control on fixation duration in reading.

The disappearing text paradigm (see Figure 5 for an illustration) is essentially the inverse of the text-onset paradigm in that text is either removed or masked after some amount of time following fixation onset (Blythe et al.,

2009; Ishida & Ikeda, 1989; Liversedge et al., 2004; Rayner et al., 1981; Rayner et al., 2003, 2006, 2011). The key finding from this paradigm is that reading is relatively unimpaired provided that the text is visible during the first 50 to 60 ms during the fixation (i.e., before it is blanked or masked). Most importantly, despite the disappearance or masking of the text, the fixation duration on the word is strongly influenced by the frequency of the word, indicating that direct lexical influences on fixation duration primarily depend on information that is extracted during the parafoveal preview period and during the first 50-60 ms of foveation on the word. In further support of the importance of parafoveal processing in the disappearing text paradigm, Rayner et al. (2006) demonstrated that simultaneous removal of the fixated word (Word *N*) and the word to the right of the fixation (Word *N+1*) substantially disrupts reading performance.

Conclusions and Future Directions

This chapter attempted to outline some of the main contours of a controversy concerning the control of the duration of fixations during reading that was over a century in the making. We would strongly argue that at the present juncture, due to the growing emphasis on computational modeling and the emerging convergence across multiple lines of empirical evidence, a consensus position can be reached which would represent true progress in this field. Specifically, given the decisive accumulated evidence for direct lexical and nonlexical influences on individual fixation durations, the current literature on the topic is beginning to transcend the existence proof stage and has instead become more focused on deriving quantitative estimates for the timing and magnitude of these influences. Such estimates constitute critical benchmarks for the development and testing of computational models of eye-movement control in reading.

Another point of emerging consensus calls into question the widely held assumption that lexical and linguistic processing are simply too sluggish to produce real-time adjustment of fixation durations (i.e., the cognitive-lag hypothesis). Specifically, when the essential role of parafoveal lexical processing is taken into account, the tight timing constraints imposed by neural delays are no longer inconsistent with the hypothesis of direct lexical control of fixation duration in reading. Based on our review, we would suggest that mechanisms of eye-movement control that are incorporated into current computational models are likely to be somewhat oversimplified. Processing of the fixated word could potentially result in both facilitatory and inhibitory influences on the timing of the saccade terminating the fixation. Furthermore, models might need to include both lexical and nonlexical direct control mechanisms (possibly combining both triggering and interference versions of direct control), as well as a variety of indirect control influences. The fact that models of eye-movement control require more than one mechanism to explain how the processing of a word influences the time spent looking at that word suggests that the term "eye-mind link" is probably a gross misnomer—to fully explain the patterns of looking times that are observed in reading, eye-movement models have to posit multiple linkages that interact in various ways.

One immediate advantage that comes from adopting this more complex perspective about how the mind interacts with the eyes is that it suggests that the models might be improved by considering how the various basic mechanisms that we have been discussing are configured in reading. Because existing models only occupy a small part of the space of possible configurations, we suspect that our understanding of eye-movement control in reading might really benefit from examining those parts of the space that have been ignored. In particular, as we argued earlier, we believe that the process-monitoring hypothesis that was first suggested by Rayner and McConkie almost 40 years ago deserves more consideration. Given the complexity just described, it is not parsimonious to assume that multiple processes and mechanisms have dedicated interfaces to the oculomotor system. It seems to us far more intuitive that at least some of the influences on fixation duration might be mediated by a system that could monitor the pattern of activation across a variety of prelexical, lexical, and postlexical processes in order to monitor their progress and infer fluency and/or difficulty without accessing the content of the various input and output representations that are involved. Such a process monitoring system could also provide a common structure for the summation of multiple influences and for interfacing with the oculomotor system. Clearly, further exploration is required in order to enhance our understanding of the nature of eye-movement control in reading.

Author Note

Correspondence regarding this chapter should be addressed to Eyal Reingold, Department of Psychology,

References

Balota, D. A., & Yap, M. J. (2011). Moving beyond the mean in studies of mental chronometry: The power of response time distributional analyses. *Current Directions in Psychological Science*, *20*, 160–166.

Becker, W., & Jürgens, R. (1979). An analysis of the saccadic system by means of double step stimuli. *Vision Research*, *19*, 967–983.

Blythe, H. I., Liversedge, S. P., Joseph, H.S.S.L., White, S. J., & Rayner, K. (2009). Visual information capture during fixations in reading for children and adults. *Vision Research*, *49*, 1583–1591.

Bouma, H., & DeVoogd, A. H. (1974). On the control of eye saccades in reading. *Vision Research*, *14*, 273–284.

Buswell, G. T. (1922). *Fundamental reading habits: A study of their development*. Chicago, IL: University of Chicago Press.

Dambacher, M., Slattery, T.J., Yang, J., Kliegl, R., & Rayner, K. (2013). Evidence for direct control of eye movements during reading. *Journal of Experimental Psychology: Human Perception and Performance*, *39*, 1468–1484.

Duffy, S. A., Kambe, G., & Rayner, K. (2001). The effect of prior disambiguating context on the comprehension of ambiguous words: Evidence from eye movements. In D. Gorfein (Ed.), *On the consequences of meaning selection: Perspectives on resolving lexical ambiguity* (pp. 27–43). Washington, DC: American Psychological Association.

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

Efron, B., & Tibshirani, R. J. (1994). *An introduction to the bootstrap*. Boca Raton, FL: Chapman & Hall.

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

Ehrlich, K. & Rayner, K. (1983). Pronoun assignment and semantic integration during reading: Eye movements and immediacy of processing. *Journal of Verbal Learning and Verbal Behavior*, *22*, 75–87.

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

Glaholt, M. G., Rayner, K., & Reingold, E. M. (2014). A rapid effect of stimulus quality on the durations of individual fixations during reading. *Visual Cognition*, *22*, 377–389.

Henderson, J. M., & Ferreira, F. (1990). Effects of foveal processing difficulty on the perceptual span in reading: Implications for attention and eye movement control. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *16*, 417–429.

Hohenstein, S., Laubrock, J., & Kliegl, R. (2010). Semantic preview benefit in eye movements during reading: A parafoveal fast-priming study. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 36, 1150–1170.

Huey, E. B. (1908). *The psychology and pedagogy of reading*. New York, NY: Macmillan.

Inhoff, A. W., Eiter, B. M., & Radach, R. (2005). Time course of linguistic information extraction from consecutive words during eye fixations in reading. *Journal of Experimental Psychology: Human Perception and Performance*, 31, 979–995.

Inhoff, A. W., & Radach, R. (2014). Parafoveal preview benefits during silent and oral reading: Testing the parafoveal information extraction hypothesis. *Visual Cognition*, *22*, 354–376.

Inhoff, A. W., & Rayner, K. (1986). Parafoveal word processing during eye fixations in reading: Effects of word frequency. *Perception & Psychophysics*, *40*, 431–439.

Ishida, T., & Ikeda, M. (1989). Temporal properties of information extraction during reading studied by a text-mask replacement technique. *Journal of Optical Society A: Optics and Image Science*, *6*, 1624–1632.

Juhasz, B. J., & Rayner, K. (2006). The role of age of acquisition and word frequency in reading: Evidence from eye fixation durations. *Visual Cognition*, *13*, 846–863.

Just, M. A., & Carpenter, P. A. (1980). A theory of reading: From eye fixations to comprehension. *Psychological Review*, *87*, 329–354.

Kennedy, A. (1998). The influence of parafoveal words on foveal inspection time: Evidence for a processing trade-off. In G. Underwood (Ed.), *Eye guidance in reading and scene perception* (pp. 149–179). Oxford, England: Elsevier.

Kennedy, A., Pynte, J., & Ducrot, S. (2002). Parafoveal-on-foveal interactions in word recognition. *Quarterly Journal of Experimental Psychology*, *55A*, 1307–1337.

Kliegl, R., Nuthmann, A., & Engbert, R. (2006). Tracking the mind during reading: The influence of past, present, and future words on fixation durations. *Journal of Experimental Psychology: General*, *135*, 12–35.

Kolers, P. A. (1976). Buswell's discoveries. In R. A. Monty & J. W. Senders (Eds.), *Eye movements and psychological processes* (pp. 373–395). Hillsdale, NJ: Lawrence Erlbaum Associates.

Liversedge, S. P., Rayner, K., White, S. J., Vergilino-Perez, D., Findlay, J. M., & Kentridge, R. W. (2004). Eye movements when reading disappearing text: is there a gap effect in reading? *Vision Research*, *44*, 1013–1024.

Luke, S. G., Nuthmann, A., & Henderson, J. M. (2013). Eye movement control in scene viewing and reading: Evidence from the stimulus onset delay paradigm. *Journal of Experimental Psychology: Human Perception and Performance*, *39*, 10–15.

Matzke, D., & Wagenmakers, E.-J. (2009). Psychological interpretation of the ex-Gaussian and shifted Wald parameters: A diffusion model analysis. *Psychonomic Bulletin & Review*, *16*, 798–817.

McConkie, G. W, Kerr, P. W., Reddix, M. D., & Zola, D. (1988). Eye movement control during reading: I. The location of initial eye fixations in words. *Vision Research*, *28*, 1107–1118.

McConkie, G. W., Kerr, P. W., Reddix, M. D., Zola, D., & Jacobs, A. M. (1989). Eye movement control during reading: II. Frequency of refixating a word. *Perception & Psychophysics*, *46*, 245–253.

McDonald, S. A., Carpenter, R.H.S., & Shillcock, R.C. (2005). An anatomically-constrained, stochastic model of eye movement control in reading. *Psychological Review*, *112*, 814–840.

Morrison, R. E. (1984). Manipulation of stimulus onset delay in reading: Evidence for parallel programming of saccades. *Journal of Experimental Psychology: Human Perception and Performance*, *10*, 667–682.

Nuthmann, A., Engbert, R., & Kliegl, R. (2005). Mislocated fixations during reading and the inverted optimal viewing position effect. *Vision Research*, *45*, 2201–2217.

Nuthmann, A., Engbert, R., & Kliegl, R. (2007). The IOVP effect in mindless reading: Experiment and modelling. *Vision Research*, *47*, 990–1002.

Nuthmann, A., & Henderson, J. M. (2012). Using CRISP to model global characteristics of fixation durations in scene viewing and reading with a common mechanism. *Visual Cognition*, *20*, 457–494.

O'Regan, J. K. (1990). Eye movements and reading. In E. Kowler (Ed.), *Eye movements and their role in visual and*

cognitive processes (pp. 395–453). Amsterdam, the Netherlands: Elsevier.

Pollatsek, A., & Rayner, K. (1990). Eye movements and lexical access in reading. In D. A. Balota, G. B. Flores d'Arcais, & K. Rayner (Eds.), *Comprehension processes in reading* (pp. 143–164). Hillsdale, NJ: Lawrence Erlbaum Associates.

Rayner, K. (1975). The perceptual span and peripheral cues in reading. *Cognitive Psychology*, 7, 65–81.

Rayner, K. (1978). Eye movements in reading and information processing. *Psychological Bulletin*, 85, 618–660.

Rayner, K. (1995). Eye movements and cognitive processes in reading, visual search, and scene perception. In J. M. Findlay, R. Walker, & R. W. Kentridge (Eds.), *Eye movement research: Mechanisms, processes and applications* (pp. 3–22). Amsterdam, the Netherlands: North Holland.

Rayner, K. (1998). Eye movements in reading and information processing: 20 years of research. *Psychological Bulletin*, 124, 372–422.

Rayner, K. (2009). The Thirty-Fifth Sir Frederick Bartlett lecture: Eye movements and attention in reading, scene perception, and visual search. *Quarterly Journal of Experimental Psychology*, 62, 1457–1506.

Rayner, K., Ashby, J., Pollatsek, A., & 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.

Rayner, K., & Duffy, S. A. (1986). Lexical complexity and fixation times in reading: Effects of word frequency, verb complexity, and lexical ambiguity. *Memory & Cognition*, 14, 191–201.

Rayner, K., Fischer, M. H., & Pollatsek, A. (1998). Unspaced text interferes with both word identification and eye movement control. *Vision Research*, 38, 1129–1144.

Rayner, K., Inhoff, A. W., Morrison, R. E., Slowiaczek, M. L., & Bertera, J. H. (1981). Masking of foveal and parafoveal vision during eye fixations in reading. *Journal of Experimental Psychology: Human Perception and Performance*, 7, 167–179.

Rayner, K., Liversedge, S. P., & White, S. J. (2006). Eye movements when reading disappearing text: The importance of the word to the right of fixation. *Vision Research*, 46, 310–323.

Rayner, K., Liversedge, S. P., White, S. J., & Vergilino- Perez, D. (2003). Reading disappearing text: Cognitive control of eye movements. *Psychological Science*, 14, 385–389.

Rayner, K., & McConkie, G. W. (1976). What guides a reader's eye movements? *Vision Research*, 16, 829–837.

Rayner, K., & Pollatsek, A. (1981). Eye movement control during reading: Evidence for direct control. *Quarterly Journal of Experimental Psychology*, 33A, 351–373.

Rayner, K., & Pollatsek, A. (1989). *The psychology of reading*. Englewood Cliffs, NJ: Prentice Hall.

Rayner, K., Sereno, S. C., & Raney, G. E. (1996). Eye movement control in reading: A comparison of two types of models. *Journal of Experimental Psychology: Human Perception and Performance*, 22, 1188–1200.

Rayner, K., Slowiaczek, M. L., Clifton, C., & Bertera, J. H. (1983). Latency of sequential eye movements: Implications for reading. *Journal of Experimental Psychology: Human Perception and Performance*, 9, 912–922.

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

Rayner, K., Yang, J., Castelhano, M. S., & Liversedge, S. P. (2011). Eye movements of older and younger readers when reading disappearing text. *Psychology and Aging*, 26, 214–223.

Reichle, E. D., & Perfetti, C. A. (2003). Morphology in word identification: A word experience model that accounts for morpheme frequency effects. *Scientific Studies of Reading*, 7, 219–237.

Reichle, E. D., Pollatsek, A., Fisher, D. L., & Rayner, K. (1998). Toward a model of eye movement control in reading. *Psychological Review*, *105*, 125–157.

Reichle, E. D., Reineberg, A. E., & Schooler, J. W. (2010). Eye movements during mindless reading. *Psychological Science*, *21*, 1300–1310.

Reichle, E. D., & Reingold, E. M. (2013). Neurophysiological constraints on the eye-mind link. *Frontiers in Human Neuroscience*, *7*, DOI: 10.3389/fnhum.2013.00361.

Reichle, E. D., Tokowicz, N., Liu, Y., & Perfetti, C. A. (2011). Testing an assumption of the E-Z Reader model of eye-movement control during reading: Using event-related potentials to examine the familiarity check. *Psychophysiology*, *48*, 993–1003.

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

Reilly, R., & Radach, R. (2006). Some empirical tests of an interactive activation model of eye movement control in reading. *Cognitive Systems Research*, *7*, 34–55.

Reingold, E. M., Reichle, E. D., Glaholt, M. G., & Sheridan, H. (2012). Direct lexical control of eye movements in reading: Evidence from a survival analysis of fixation durations. *Cognitive Psychology*, *65*, 177–206.

Reingold, E. M., & Rayner, K. (2006). Examining the word identification stages hypothesized by the E-Z Reader model. *Psychological Science*, *17*, 742–746.

Reingold, E. M., & Stampe, D. M. (1999). Saccadic inhibition in complex visual tasks. In W. Becker, H. Deubel, & T. Mergner (Eds.), *Current oculomotor research: Physiological and psychological aspects* (pp. 249–255). London, England: Plenum.

Reingold, E. M., & Stampe, D. M. (2000). Saccadic inhibition and gaze contingent research paradigms. In A. Kennedy, R. Radach, D. Heller, & J. Pynte (Eds.), *Reading as a perceptual process* (pp. 119–145). Amsterdam, the Netherlands: Elsevier.

Reingold, E. M., & Stampe D. M. (2002). Saccadic inhibition in voluntary and reflexive saccades. *Journal of Cognitive Neuroscience*, *14*, 371–388.

Reingold, E. M., & Stampe, D. M. (2003). Using the saccadic inhibition paradigm to investigate saccadic control in reading. In J. Hyona, R. Radach, & H. Deubel (Eds.), *The mind's eye: Cognitive and applied aspects of eye movements* (pp. 347–360). Amsterdam, the Netherlands: Elsevier.

Reingold, E. M., & Stampe D. M. (2004). Saccadic inhibition in reading. *Journal of Experimental Psychology: Human Perception and Performance*, *30*, 194–211.

Reingold, E. M., Yang, J., & Rayner, K. (2010). The time course of word frequency and case alternation effects on fixation times in reading: Evidence for lexical control of eye movements. *Journal of Experimental Psychology: Human Perception and Performance*, *36*, 1677–1683.

Risse, S., & Reinhold, K. (2012). Evidence for delayed parafoveal-on-foveal effects from word $n + 2$ in reading. *Journal of Experimental Psychology: Human Perception & Performance*, *38*, 1026–1042.

Salvucci, D. D. (2001). An integrated model of eye movements and visual encoding. *Cognitive Systems Research*, *1*, 201–220.

Schad, D. J., Nuthmann A., & Engbert, R. (2012). Your mind wanders weakly, your mind wanders deeply: Objective measures reveal mindless reading at different levels. *Cognition*, *125*, 179–194.

Schad, D. J., Risse, S., Slattery, T., & Rayner, K. (2014). Word frequency in fast priming: Evidence for immediate cognitive control of eye movements during reading. *Visual Cognition*, *22*, 390–414.

Sheridan, H., Rayner, K., & Reingold, E. M. (2013). Unsegmented text delays word identification: Evidence from a

survival analysis of fixation durations. *Visual Cognition*, *21*, 38–60.

Sheridan, H., & Reingold, E. M. (2012a). The time course of predictability effects in reading: Evidence from a survival analysis of fixation durations. *Visual Cognition*, *20*, 733–745.

Sheridan, H., & Reingold, E. M. (2012b). The time course of contextual influences during lexical ambiguity resolution: Evidence from distributional analyses of fixation durations. *Memory & Cognition*, *40*, 1122–31.

Sheridan, H., & Reingold, E. M. (2013). A further examination of the lexical processing stages hypothesized by the E-Z Reader model. *Attention*, *Perception*, *& Psychophysics*, 75, 407–414.

Sheridan, H., Reingold, E. M., & Daneman, M. (2009). Using puns to study contextual influences on lexical ambiguity resolution: Evidence from eye movements. *Psychonomic Bulletin & Review*, *16*, 875–881.

Slattery, T. J., Angele, B., & Rayner, K. (2011). Eye movements and display change detection during reading. *Journal of Experimental Psychology: Human Perception and Performance*, *37*, 1924–1938.

Staub, A. (2011). The effect of lexical predictability on distributions of eye fixation durations. *Psychonomic Bulletin & Review*, *18*, 371–376.

Staub, A., & Benatar, A. (2013). Individual differences in fixation duration distributions in reading. *Psychonomic Bulletin & Review*, 20, 1304–1311.

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

Tinker, M. A. (1958). Recent studies of eye movements in reading. *Psychological Bulletin*, *55*, 215–231.

Vitu, F., Lancelin, D., & d'Unienville, V. M., (2007). A perceptual-economy account for the inverted-optimal viewing position effect. *Journal of Experimental Psychology: Human Perception and Performance*, 33, 1220–1249.

Vitu, F., McConkie, G. W., Kerr, P., & O'Regan, J. K. (2001). Fixation location effects on fixation durations during reading: An inverted optimal viewing position effect. *Vision Research*, *41*, 3511–3531.

White, S. J. (2008). Eye movement control during reading: Effects of word frequency and orthographic familiarity. *Journal of Experimental Psychology: Human Perception and Performance*, *24*, 205–223.

White, S. J., & Staub, A. (2012). The distribution of fixation durations during reading: Effects of stimulus quality. *Journal of Experimental Psychology: Human Perception and Performance*, *38*, 603–617.

Yang, S.-N., & McConkie, G. W. (2001). Eye movements during reading: A theory of saccade initiation times. *Vision Research*, *41*, 3567–3585.

Eyal M. Reingold

Eyal M. Reingold is a professor in the Department of Psychology at the University of Toronto in Canada.

Heather Sheridan

Heather Sheridan is a professor in the Department of Psychology at the University of Toronto in Canada.

Erik D. Reichle

Erik D. Reichle is Professor of Cognitive Psychology at University of Southampton.