The Time-course of Lexical Influences on Fixation Durations during Reading: Evidence from Distributional Analyses

Heather Sheridan

Doctor of Philosophy

Department of Psychology
University of Toronto

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Abstract

Competing models of eye movement control during reading disagree over the extent to which eye movements reflect ongoing linguistic and lexical processing, as opposed to visual/oculomotor factors (for reviews, see Rayner, 1998, 2009a). To address this controversy, participants’ eye movements were monitored in four experiments that manipulated a wide range of lexical variables. Specifically, Experiment 1 manipulated contextual predictability by presenting target words (e.g., teeth) in a high-predictability prior context (e.g. “The dentist told me to brush my teeth to prevent cavities.”) versus a low-predictability prior context (e.g., “I'm planning to take better care of my teeth to prevent cavities.”), Experiment 2 manipulated lexical ambiguity by presenting biased homographs (e.g., bank, crown, dough) in a subordinate-instantiating versus a dominant-instantiating prior context, and Experiments 3A and 3B manipulated word frequency by contrasting high frequency target words (e.g., table) and low frequency target words (e.g., banjo). In all four experiments, I used distributional analyses to examine the time-course of lexical influences on fixation times. Ex-Gaussian fitting (Staub, White, Drieghe, Hollway, & Rayner, 2010) revealed that all three lexical variables (i.e., predictability, lexical ambiguity, word frequency) were fast-acting enough to shift the entire distribution of fixation times, and a survival analysis technique (Reingold, Reichle, Glaholt, &
Sheridan, 2012) revealed rapid lexical effects that emerged as early as 112 ms from the start of the fixation. Building on these findings, Experiments 3A and 3B provided evidence that lexical processing is delayed in an unsegmented text condition that contained numbers instead of spaces (e.g., “John4decided8tosell9the7table2in3the9garage6sale”), relative to a normal text condition (e.g., “John decided to sell the table in the garage sale”). These findings have implications for ongoing theoretical debates concerning eye movement control, lexical ambiguity resolution, and the role of interword spaces during reading. In particular, the present findings provide strong support for models of eye movement control that assume that lexical influences can have a rapid influence on the majority of fixation durations, and are inconsistent with models that assume that fixation times are primarily determined by visual/oculomotor constraints.
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1 Introduction

Reading is a complex skill that taps a wide range of visual, oculomotor, attentional, language and memory processes. During fluent reading, these diverse processes are coordinated to produce reading behaviour that is often remarkably effortless and efficient. In an attempt to understand the processes underlying reading, a considerable body of research has measured the eye movements of skilled readers. Eye movements are an essential component of reading (as well as other visual tasks) because humans must move their eyes to compensate for the fact that the human eye can only see detail in a small region of the retina called the fovea. During reading, high velocity eye movements (referred to as saccades) occur approximately 3-4 times a second, and are separated by fixations during which the eyes are relatively still and perceptual information is extracted (Rayner, 1998). Eye movements during reading are sensitive to a wide range of perceptual and cognitive variables, and eye movements can provide rich and informative time-course information about these variables (for reviews, see Rayner, 1998, 2009a).

Given the importance of eye movements during skilled reading, extensive empirical and theoretical efforts have been directed at developing models of eye movement control during reading (for reviews, see Rayner, 1998, 2009a). These models attempt to simulate and explain the cognitive, oculomotor and perceptual 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 controversy among models of eye movement control concerns the degree to which higher-level cognitive processes can impact fixation durations (i.e., the when decisions) during reading. In this debate, oculomotor theories assume that non-lexical, low-level visual information and
oculomotor constraints determine eye movement control in reading (e.g., McConkie, Kerr, Reddix, & Zola, 1988; McConkie, Kerr, Reddix, Zola, & Jacobs, 1989; O’Regan, 1990, 1992), whereas processing theories instead assume that higher-level lexical, linguistic and attentional processes can produce a fast acting and non-trivial impact on fixation durations (e.g., Henderson & Ferreira, 1990; Just & Carpenter, 1980; Kennison & Clifton, 1995; Morrison, 1984; Rayner & Pollatsek, 1989).

In light of this controversy, the main goal of this thesis is to examine the role of lexical influences in driving fixation durations during reading. Accordingly, I will begin by reviewing the history of the controversy over the nature of cognitive influences on when decisions during reading. I will then discuss contemporary views on this controversy, which now focuses primarily on the time-course of lexical influences, and the question of whether lexical influences can be fast-acting enough to impact the majority of fixations rather than a subset of long fixation times. Finally, I will introduce several distributional analyses of fixation durations (Reingold, Reichle, Glaholt, & Sheridan, 2012; Staub, White, Drieghe, Hollway, & Rayner, 2010) that will be used to address the ongoing controversy over the time-course of lexical influences on fixation durations.

1.1 The eye-mind link

There has been long-standing controversy over the relationship between eye movements and moment-to-movement thought processes (i.e., the eye-mind link). The issue of the eye-mind link has theoretical importance to models that attempt to understand the processes underlying reading, as well as methodological importance to researchers that use eye tracking as a dependent measure. Indeed, the extensive use of eye tracking as a methodology for studying cognitive processes in reading presupposes that there is a least a loose relationship between eye
movements and ongoing cognitive processing. Thus, it is important to elucidate the precise link between eye movements and cognition during reading.

To understand the eye-mind link during reading, it is necessary to determine the underlying processes that control the moment-to-moment “decisions” about when and where to move the eyes. Accordingly, researchers have spent over a century debating and investigating the factors that influence eye movement control during reading (for reviews, see Rayner, 1998, 2009a, 2009b; Starr & Rayner, 2001; Tinker, 1936, 1946, 1958). As discussed by Rayner and McConkie (1976), these debates have historically distinguished between higher level and lower-level influences on eye movement control. Low-level influences encompass processes that are closely tied to the perceptual input (e.g., visual and oculomotor processes), whereas higher-level influences reflect cognitive processes that are less directly tied to the perceptual input, and instead involve previously-stored information (e.g., lexical, semantic, and syntactic processing). A “strong” or a “tight” eye-mind link would mean that ongoing cognitive processing plays a major role in controlling eye movements. In contrast, a “weak” or a “loose” eye-mind link implies that ongoing cognitive processing plays a more subsidiary role, and that eye movements primarily reflect low-level influences and/or random variation.

Prior to the 1980s, there was a great deal of skepticism over whether higher-level cognitive processes could impact eye movements. In part, this skepticism stemmed from failures to show a link between eye movements and the properties of the fixated text. For example, Morton (1964) reported that average fixation durations did not vary across text passages that varied in difficulty level, which corroborated earlier findings that fixation times tended to remain stable across conditions (e.g., for a review, see Tinker, 1938). In fact, it was commonly believed that skilled reading was characterized by a consistent and non-variable
pattern of forward eye movements, with the exception of occasional regressions (Tinker, 1938). In line with this view, Buswell (1937) emphasized that mature readers display regular and rhythmic eye movements, and Taylor (1937) developed techniques to help readers to develop a constant and rhythmic pattern of eye movements. Tinker (1938) speculates that this focus on the eye movement record itself as a marker of skilled reading may have led to a neglect of other aspects of the reading process, such as comprehension. Moreover, as noted by Rayner (1998), the behaviorist movement in experimental psychology may have further contributed to the prevailing focus on observable eye movement behaviour rather than on higher-level cognitive processes. Further compounding these issues, the eye tracking equipment that was available at the time might have failed to detect some of the variations in fixation times across conditions. As discussed by Rayner and Pollatsek (1989), the early eye trackers were less accurate, and it was difficult to collect and analyze large datasets prior to the advent of modern computers.

Another source of skepticism concerning a strong eye-mind link was the argument that there wasn’t enough time during a fixation for ongoing cognitive processing to influence saccade timing. According to this argument, it is not feasible for lexical influences to be fast-acting enough to play a non-trivial role in impacting fixation times, because of the tight temporal constraints inherent to the visual and oculomotor systems (Sereno & Rayner, 2003). Specifically, at the start of a new fixation, it takes an estimated 50 ms for visual information to propagate from the eye to the brain (i.e., the ‘‘eye-to-brain’’ lag; Clark, Fan, & Hillyard, 1995; Foxe & Simpson, 2002; Mouchetant-Rostaing, Giard, Bentin, Aguera, & Pernier, 2000; Van Rullen & Thorpe, 2001). As well, due to the oculomotor latency required to program an eye movement (i.e., the interval between the initiation of programming and the execution of a saccade), lexical processing occurring during the final 100 – 150 ms of a given fixation cannot influence the timing of the saccade that ends that fixation. Given these temporal constraints,
there has been a great deal of skepticism over whether it is possible for higher-level lexical and linguistic processing to be fast-acting enough to modulate fixation times that are only 200 to 250 ms on average.

1.2 Oculomotor theories

In light of these arguments against a strong-mind link, there was a great deal of support for oculomotor theories (e.g., McConkie et al., 1988, 1989; O’Regan, 1990, 1992), which assumed that eye movements were driven by non-lexical, low-level properties of the fixated text (e.g., word length, word boundaries, etc.) as well as by visual and oculomotor constraints (e.g., limits to visual acuity, oculomotor error, etc.). In particular, oculomotor theories have provided a detailed account of “where” decisions (i.e., fixation locations) during reading. According to this account, readers learn to aim their eyes towards the center of each word (i.e., the optimal viewing position; O’Regan, 1992) because word recognition is most rapid when the center of the word is fixated. However, due to oculomotor error, the mean location of initial fixations on a word tends to be slightly to the left of the word’s centre (i.e., the preferred viewing location; Rayner, 1979). With regards to “when” decisions (i.e., fixation durations), oculomotor theories assume that fixation times are primarily determined by low-level variables, such as word length and fixation location. For example, fixation durations increase as word length increases (e.g., Just & Carpenter, 1980; Rayner, Sereno, & Raney, 1996), and the initial fixation on a word (i.e., first-fixation duration) is longer for fixations located near the center of the word than for fixations near the beginning or the end of the word (i.e., the inverted optimal viewing position effect; Vitu, 2001). In sum, oculomotor theories emphasize that low-level variables are primarily responsible for guiding eye movements and that higher-level cognitive influences have a weak or minimal impact on eye movements.
However, theories that only included low-level influences could not accommodate emerging findings that cognitive and contextual variables could also impact eye movements. In the early literature, such cognitive variables included the difficulty level of the text, the task requirements and instructions, and the skill level of the reader (for reviews, see Tinker, 1936, 1946, 1958). For example, fixation durations can depend on the type of text that is being read, such that fixation durations are longer and more variable for difficult prose relative to easy prose (Tinker, 1958). More specifically, Tinker (1958) 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. For instance, in reading without attention to meaning, pause durations are brief and constant while for reading algebraic problems they are long and variable.” (p. 218)

Thus, according to Tinker (1958), fixation durations during reading reflect both perceptual and cognitive processes.

1.3 Direct versus Indirect control

Due to the growing evidence in support of cognitive influences, it was necessary for models of eye movement control to reconcile cognitive influences on fixation times with the wide-spread assumption that cognitive influences were too sluggish to impact fixation times. One solution to this problem is to assume that cognitive and lexical influences can produce a delayed adjustment (i.e., non-real-time) of fixation times based on the average processing difficulty and other contextual factors (i.e., indirect control) rather than an immediate fixation-by-fixation adjustment based on the properties of the local stimulus (i.e. direct control). The advantage of indirect cognitive control is that it circumvents the issue of temporal constraints by assuming that cognitive influences on fixation times are delayed rather than immediate. Several early variants of indirect control were incorporated into gain control models (e.g., Kolers, 1976),
which assumed that fixation times varied randomly around a pre-set rate that (on average) allowed enough time to encode the text, and buffer control models (e.g., Bouma & Voogd, 1974), which assumed that eye movements were controlled by the contents of a “cognitive buffer” that stored information that was not fully processed on previous fixations. According to the buffer control models, readers maintain an optimal rate of eye movements by increasing the speed of their eye movements whenever the cognitive buffer is empty, and decreasing the speed of their eye movements whenever the cognitive buffer is full. These models could accommodate the effects shown by cognitive and contextual variables (i.e., text difficulty, skill level of the reader, etc.) without requiring fast-acting cognitive influences.

1.4 Processing theories

Advances in eye tracking technology produced new findings that could not be easily explained by indirect control mechanisms or by oculomotor theories, and were instead interpreted as support for processing theories (e.g., Henderson & Ferreira, 1990; Just & Carpenter, 1980; Kennison & Clifton, 1995; Morrison, 1984; Rayner & Pollatsek, 1989). According to processing theories, there is a strong link between eye movements and cognition, such that fixation times are driven by ongoing higher level attentional, linguistic and lexical processing. In support of this viewpoint, there is now a great deal of empirical evidence that higher level cognitive processing can impact fixation durations (for reviews, see Rayner, 1998, 2009a).

To test whether ongoing cognitive processing could impact fixation times, Rayner and Pollatsek (1981) used a visual mask to delay the onset of the foveal text for a random amount of time at the start of each fixation. Fixation times varied according to the duration of the mask, even though readers could not predict the duration of the mask in advance of the fixation.
Rayner and Pollatsek (1981) argued that this finding supports the processing perspective by demonstrating that fixation durations can be modulated from fixation to fixation in response to ongoing cognitive processing.

In addition, the *disappearing text procedure* provided strong evidence for the processing perspective (Blythe, Liversedge, Joseph, White, & Rayner, 2009; Ishida & Ikeda, 1989; Liversedge et al., 2004; Rayner, Inhoff, Morrison, Slowiaczek, & Bertera, 1981; Rayner, Liversedge, White, & Vergilino-Perez, 2003). In this procedure, the fixated word is removed 60 ms after the start of the fixation. Remarkably, word frequency effects on fixation durations remained intact such that readers remained fixated on the location where the word had been longer for low frequency words relative to high frequency words. Rayner and colleagues interpreted these results as strong evidence that ongoing lexical information drives fixation durations during reading.

Building on previous evidence for fast acting cognitive influences, there is now a large body of evidence that fixation times are influenced by higher-level lexical and/or linguistic variables. Such lexical effects include word frequency (Inhoff & Rayner, 1986; Rayner & Duffy, 1986; see White, 2008 for a review), contextual constraint or predictability (Ehrlich & Rayner, 1981; Rayner, Ashby, Pollatsek, & Reichle, 2004; Rayner & Well, 1996), lexical ambiguity (e.g., Duffy, Morris, & Rayner, 1988; Rayner & Duffy, 1986; Sheridan, Reingold, & Daneman, 2009; see Duffy, Kambe, & Rayner, 2001 for a review) and age of acquisition (e.g., Juhasz & Rayner, 2006). These effects were shown for a variety of first-pass fixation time measures, including gaze duration (i.e., the sum of all of the first-pass fixations on the target word), single fixation (i.e., gaze duration for the subset of trials with only one fixation on the target word), first fixation (i.e., the first fixation on the target word), and the duration of the first
of multiple first-pass fixations. As discussed by Reingold, Yang, and Rayner (2010), these early lexical effects support direct cognitive control by indicating that lexical properties of the currently fixated word can have a rapid influence on fixation durations. Importantly, it is difficult for indirect control mechanisms to account for such fast-acting effects, and it is difficult for oculomotor models to account for the fact that these lexical effects still emerged even when low-level variables (e.g., word length) were held constant across conditions.

Consequently, these lexical and linguistic effects formed the impetus for the development of processing models. An early example of a processing model was implemented by the Reader model (Just & Carpenter, 1980, 1987; Thibadeau, Just, & Carpenter, 1982). The Reader model incorporates two strong assumptions concerning the link between eye movements and ongoing cognitive processing. According to the *immediacy assumption*, readers will attempt to interpret each word as soon it is encountered, even though this initial “guess” may occasionally turn out to be wrong in light of subsequent visual, lexical, semantic or syntactic processing. Moreover, according to the *eye-mind assumption*, the currently fixated word (i.e., $\text{word}_n$) is processed completely before the eyes move to the next word (i.e., $\text{word}_{n+1}$). This processing was assumed to include word identification, as well as any syntactic and semantic processing that was required to integrate the word’s meaning into the overall meaning of the text being constructed by the reader. Based on this account, fixation time data can be easily interpreted because the sum of all the first-pass fixations on a word (i.e., *gaze duration*) can be assumed to reflect the amount of time required to process the word.

However, the Reader model’s extreme assumptions were shown to be incompatible with emerging empirical findings (e.g., Ehrlich & Rayner, 1983), as well as the temporal constraints imposed by word identification and saccadic programming. Consequently, more recent models
have adopted less extreme assumptions concerning the amount of cognitive processing that is required before the eyes will move forward in the text. For example, eye movements are triggered by the completion of lexical access in the model proposed by Morrison (1984), by the encoding of word$_n$ in the EMMA model (Salvucci, 2001) and by the completion of an early stage of lexical processing in the E-Z Reader model (Reichle, Pollatsek, Fisher, & Rayner, 1998). Moreover, even less cognitive processing is necessary to initiate saccadic programming in the SERIF model (McDonald, Carpenter, & Shillcock, 2005) and the Glenmore model (Reilly & Radach, 2006), which both include the assumption that visual word encoding results in the triggering of saccades.

1.5 The E-Z Reader model

Out of the models discussed thus far, the E-Z Reader model (Reichle et al., 1998) is perhaps the most influential processing model. Similar to Morrison (1984), the E-Z Reader model assumed that words are processed one at a time, in a strictly serial manner (Reichle, 2011; see also Reichle, Liversedge, Pollatsek, & Rayner, 2009), and that lexical processing is the “engine” that drives eye movements from word to word. However, unlike the model proposed by Morrison (1984), the E-Z Reader model introduced a distinction between two stages of lexical processing (i.e., L$_1$ and L$_2$). Specifically, the E-Z Reader model assumes that the initiation of the programming of a saccade to the next word (word$_{n+1}$) is triggered by an early stage of lexical processing (L$_1$), which indicates that lexical access is imminent. Lexical processing of word$_n$ is then completed during a subsequent stage of lexical processing (L$_2$) and the conclusion of this stage causes covert attention to shift to word$_{n+1}$. The precise nature of the L$_1$ and L$_2$ stages remains controversial, but it has been hypothesized that L$_1$ reflects either a rapid assessment of word familiarity (Reichle, Tokowicz, Liu, & Perfetti, 2011) or an early stage of orthographic
processing, whereas $L_2$ reflects a later stage of lexical and/or postlexical processing. As reviewed by Rayner (1998), the E-Z Reader has successfully accommodated a wide range of empirical findings, and has generated novel predictions (e.g., Reingold & Rayner, 2006).

### 1.6 The SWIFT model

One of the main contenders to the E-Z Reader model is the SWIFT model (i.e., Saccade-generation With Inhibition by Foveal Targets; Engbert, Longtin, & Kliegl, 2002; Engbert, Nuthmann, Richter, & Kliegl, 2005). Unlike the E-Z Reader model’s serial processing assumption, SWIFT assumes that attention can be allocated to several words simultaneously (a similar parallel processing assumption was adopted by the Glenmore model; Reilly & Radach, 2003). Moreover, according to SWIFT, saccades are triggered by an autonomous random timer, but lexical processing difficulty associated with the currently fixated word ($\text{word}_n$) can lengthen fixation times by actively inhibiting this timer so that it cannot initiate new saccadic programs (this process is known as foveal inhibition). Given that recent versions of SWIFT have incorporated a time delay in the foveal inhibition process (see Engbert et al., 2005), any difficulty associated with the processing of $\text{word}_n$ usually results in a longer fixation on $\text{word}_{n+1}$ (i.e., spillover effects) rather than on $\text{word}_n$. Nevertheless, foveal inhibition can still be classified as a form of direct cognitive control because it is based on local processing and it can (at least occasionally) impact fixation durations on $\text{word}_n$. Thus, similar to the E-Z Reader model, the SWIFT model can accommodate lexical and linguistic effects on fixation times.

### 1.7 Controversy over the time-course of lexical influences

Although lexical influences have been incorporated into models of eye movement control, there continues to be controversy over the time-course of these influences, and the proportion of fixations that are impacted. Critics of the processing perspective continue to argue
that it is not feasible for lexical influences to be fast-acting enough to play a non-trivial role in impacting fixation times, because of the tight temporal constraints inherent to the visual and oculomotor systems (Sereno & Rayner, 2003). Instead, these critics argue that lexical influences on mean fixation times are due to a small proportion of long fixations, rather than a fast acting influence on the majority of fixation times. For instance, the *Competition-Interaction model* (McConkie & Yang, 2003; Yang & McConkie, 2001, 2004) assumes that cognitive and linguistic processing is too slow to modulate the majority of fixation times. Instead, this model assumes that lexical processing difficulty can occasionally cause programmed saccades to be delayed or cancelled, which results in an increase in the proportion of long fixation durations. Thus, models of eye movement control continue to disagree over whether lexical influences are fast-acting enough to influence the vast majority of fixation times as opposed to a subset of long fixation durations.

### 1.8 Distributional analyses of fixation times

One method for addressing this ongoing controversy over the time course of lexical influences is to examine distributions of fixation times. Distributional analyses can provide fine-grained time-course information that is not available from mean fixation analyses alone. In particular, ex-Gaussian fitting (Staub et al., 2010) and a survival analysis technique (Reingold et al., 2012) were recently used to provide valuable information about the time-course of lexical influences during reading.

As discussed by Staub et al. (2010), ex-Gaussian fitting can reveal whether a variable’s impact on mean fixation times is due to a shift in the location of the distribution and/or a change in the degree of skew. Whereas a shift effect indicates that the variable is having an early acting influence on the majority of fixation durations, a skew effect primarily stems from an influence
on long fixation durations. Staub et al. (2010) fitted the ex-Gaussian distribution (Ratcliff, 1979) to individual participants’ distributions of fixation times on both high frequency and low frequency target words. The word frequency variable produced a shift effect such that the distributions of fixation times for low frequency words were shifted to the right of the distribution for high frequency words, as well as a skew effect such that the low frequency distribution exhibited greater positive skew (right skew) as compared to the high frequency distribution. More recently, Staub et al. (2011) demonstrated a shift effect (but not a skew effect) for the predictability variable, such that the distribution of fixation times was shifted to the right when target words were encountered in a low predictability context relative to a high predictability context. Staub and colleagues interpreted these ex-Gaussian findings as support for direct lexical control, because both lexical variables (i.e., predictability and word frequency) were fast-acting enough to produce a shift in the entire distribution of fixation times, rather than long fixation times alone.

Building on the earlier work by Staub and colleagues, Reingold et al. (2012) examined the time-course of word frequency effects using a novel survival analysis technique. Specifically, for a given time $t$, the percentage of first fixations with a duration greater than $t$ are referred to as the percent survival at time $t$. Thus, when $t$ equals zero, survival is at one hundred percent, but then declines as $t$ increases and approaches zero percent as $t$ approaches the duration of the longest observed first fixation. Reingold et al. (2012) calculated survival curves separately for each condition (i.e., high frequency vs. low frequency) in order to examine the earliest point at which the high and low frequency curves first started to diverge (henceforth referred to as the divergence point). Importantly, Reingold et al. (2012) argued that the divergence point provided an estimate of the earliest significant influence of the word frequency variable.
Reingold et al. (2012) employed this survival analysis technique, as well as ex-Gaussian fitting, to test their hypothesis that rapid lexical influences on fixation times are possible because readers begin to process upcoming target words during fixations on the pre-target word (i.e., \textit{parafoveal processing}). To directly manipulate parafoveal processing, Reingold et al. (2012) employed the \textit{gaze-contingent boundary paradigm} (Rayner, 1975) to contrast invalid and valid preview trials. For 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, for the preview condition, the target words were presented under normal reading conditions, such that the target word was always displayed through the trial. Using this paradigm, Reingold et al. (2012) demonstrated that the temporal onset of word frequency effects was delayed for the invalid preview condition relative to the valid preview (i.e., normal reading) condition. Specifically, the survival analysis revealed that the high and low frequency curves first began to diverge at 145 ms in the valid condition, and at 256 ms in the invalid preview condition. This finding was corroborated by the ex-Gaussian analysis, which produced a shift and a skew effect for the valid condition (in replication of Staub et al., 2010), but a skew effect only for the invalid condition. Taken together, these results indicate that parafoveal processing plays a crucial role in enabling direct cognitive control of fixation times during normal reading.

1.9 Overview of the thesis

The main goal of this thesis is to employ the ex-Gaussian fitting (Staub et al., 2010) and survival analysis (Reingold et al., 2012) techniques to address several ongoing controversies concerning the time-course of lexical influences on fixation durations during reading. In Experiments 1 and 2, I examined whether the early word frequency effects reported by Reingold
et al. (2012), could be extended to two additional lexical variables: predictability (Experiment 1), and lexical ambiguity (Experiment 2). The predictability variable was selected because it is assumed to be a key determiner of fixation durations in both the E-Z Reader (Reichle et al., 1998) and SWIFT models (Engbert et al., 2002, 2005). Moreover, given that Staub et al. (2010) has already demonstrated a shift effect for the predictability variable, I wished to see if this early effect on fixation durations could be replicated and extended using the survival analysis technique introduced by Reingold et al. (2012). In addition, I examined the lexical ambiguity variable in Experiment 2 because it has played a central role in ongoing theoretical debates over whether prior contextual information can modulate the early lexical access stage of reading rather than a postlexical integration stage (for a review, see Duffy et al., 2001). Given that the lexical ambiguity literature has not yet used distributional analysis techniques to address this issue, I wished to explore whether such techniques could provide insights concerning the time-course of contextual influences on lexical ambiguity resolution.

Finally, in Experiment 3, I employed distributional analyses to examine the role of interword spaces during reading, by testing a specific prediction that removing interword spaces (i.e, unsegmented text) interferes with lexical processing (Rayner et al., 1998). To test this prediction, I examined whether the survival analysis technique would reveal a later temporal onset of word frequency effects for unsegmented text relative to normal text conditions. Thus, the overall goal of my thesis was to explore the time-course of lexical influences on fixation durations under a wide range of conditions in order to resolve ongoing controversies concerning the nature of eye movement control (Experiments 1 and 2), the mechanisms underlying lexical ambiguity resolution (Experiment 2), and the role of interword spaces during reading (Experiments 3A and 3B).
2 Experiment 1

Fixation times during reading are influenced by a variety of lexical and linguistic variables (for reviews, see Rayner, 1998, 2009a), including word frequency (see White, 2008, for a review) and predictability (i.e., contextual constraints; Ehrlich & Rayner, 1981). With respect to the word frequency variable, it is well-established that fixation times are shorter on words that are common in the English language (e.g., table), relative to words that are less frequent (e.g., banjo), and this finding still occurs even after controlling for potentially confounding variables, such as word length and orthographic familiarity (White, 2008). In addition, predictability effects have been commonly shown such that fixation times on target words (e.g., teeth) are shorter in a high predictability prior context (e.g., “The dentist told me to brush my teeth to prevent cavities”) relative to a low predictability prior context (e.g., “I'm planning to take better care of my teeth to prevent cavities”), and this finding persists even when word length and word frequency are equated across conditions (e.g., Ehrlich & Rayner, 1981; Rayner et al., 2004; Rayner & Well, 1996).

As reviewed by Rayner (1998, 2009a), these two lexical effects (i.e., word frequency and predictability) are widely considered to be benchmark findings that must be accounted for by models of eye movement control during reading. However, competing models differ considerably in their assumptions concerning the time course of lexical effects. Specifically, one class of models assumes that fixation times are primarily driven by visual/oculomotor factors and that lexical variables can only impact a small subset of long fixations (e.g., Deubel, O’Regan, & Radach, 2000; Feng, 2006, 2012; McConkie & Yang, 2003; Yang, 2006; Yang & McConkie, 2001), whereas a competing class of models assumes that lexical and linguistic processes play a
non-trivial role in controlling fixation times in reading (e.g., Engbert et al., 2002, 2005; Just & Carpenter, 1980, 1987; Kliegl & Engbert, 2003; McDonald et al., 2005; Morrison, 1984; Pollatsek, Reichle, & Rayner, 2006; Reichle et al., 1999; 2003, 2006; Reilly & Radach, 2003, 2006; Reingold et al., 2010; Richter et al., 2006; Thibadeau et al., 1982)

To help distinguish between the competing time course assumptions of the various models, recent work has employed distributional analyses of fixation times during reading (Reingold et al., 2012; Staub et al., 2010; Staub, 2011; White, Staub, Drieghe, & Liversedge, 2011; White & Staub, 2012; White, Warren, Staub, & Reichle, 2011). In particular, Staub et al. (2010) introduced ex-Gaussian fitting as a technique for modeling individual participants’ distributions of fixation times during reading. A key advantage of ex-Gaussian fitting is that it clarifies whether a variable’s impact on mean fixation times is due to a shift in the location of the distribution and/or a change in the degree of skew. As explained by Staub et al. (2010), a shift effect indicates that the variable is having an early acting influence on the majority of fixation durations, whereas a skew effect primarily stems from an influence on long fixation durations. In support of an early time course of lexical effects, both the word frequency variable (Reingold et al., 2012; Staub et al., 2010) and the predictability variable (Staub, 2011) have been shown to produce a shift effect.

In addition to ex-Gaussian fitting, another distributional analysis approach has examined survival curves of first-fixation durations during reading (Reingold et al., 2012). Specifically, for a given time $t$, the percentage of first fixations with a duration greater than $t$ are referred to as the percent survival at time $t$. Thus, when $t$ equals zero, survival is at one hundred percent, but then declines as $t$ increases and approaches zero percent as $t$ approaches the duration of the longest observed first fixation. Reingold et al. (2012) examined the time course of word frequency
effects during reading by calculating separate survival curves for first-fixation durations on low
frequency and high frequency target words. They then examined the earliest point in time at
which the high and low frequency survival curves began to significantly diverge (i.e., the
divergence point). Importantly, Reingold et al. (2012) argued that the divergence point provided
an estimate of the earliest significant influence of the word frequency variable. Based on their
survival curve analyses, they concluded that there is a significant influence of word frequency on
fixation duration in normal reading as early as 145 ms from the start of fixation (for other
applications of survival curves, see Glaholt & Reingold, 2012; Feng, Miller, Shu, & Zhang,
2001; see also Reingold & Sheridan, 2011, for a review of the use of survival analysis in the
study of visual expertise).

The main goal of this experiment is to employ the survival analysis technique (Reingold
et al., 2012) to study the time course of the influence of predictability on first-fixation duration.¹
Specifically, the same target words were read once in a low predictability context and once in a
high predictability context. Using the technique introduced by Reingold et al. (2012), I
examined survival curves for the distributions of first-fixation durations on target words in the
low and high predictability contexts, and I then calculated the divergence point for the low and
high predictability curves in order to provide an estimate of the earliest significant influence of
the predictability manipulation. Given that ex-Gaussian analyses have demonstrated a shift effect
for predictability (Staub, 2011), I predicted that a survival analysis might indicate a divergence
point that would be equally as early for the present study’s predictability manipulation as it was

¹ For the distributional analyses, I used the first-fixation duration measure because it provides more data
than the single-fixation measure. First-fixation duration is the duration of the first forward fixation on a
word regardless of the number of subsequent fixations on the word, whereas single-fixation duration is
the first-fixation value for the subset of trials in which there was only one first-pass fixation on the word.
for the word frequency manipulation reported by Reingold et al. (2012). Such a finding would provide convergent evidence for an early time course of lexical variables during reading.

2.1 Method

Participants

All 60 undergraduate students at the University of Toronto who participated were native English speakers and were given either course credit or $10 (Canadian) per hour. All had normal or corrected-to-normal vision.

Materials

As shown in Appendix A, 40 sentence pairs were created such that a target word (e.g., “muscle”) was either highly predictable (e.g., “The athlete pulled a muscle in his leg during the competition.”) or unpredictable (e.g., “Peter says that a muscle in his leg was bothering him during soccer practice.”). To obtain cloze norms² for these sentence pairs, an independent sample of 20 undergraduates were given the sentence frames up to but not including the target words, and they were asked to produce the word that seemed most likely to come next in the sentence. The high predictability sentences had a mean cloze probability of .78 (range = .5 to 1).

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² These norms were collected using the cloze task (W. L. Taylor, 1953), which is a common method of assessing the predictability of a word in context (for alternative methods, see e.g., McDonald & Shillcock, 2003; Wang, Pomplun, Chen, Ko, & Rayner, 2010). In the cloze task, participants are given the sentence frames up to but not including the target words, and they are asked to generate the word that seems most likely to come next in the sentence. Predictability is then assessed by calculating the proportion of times that each sentence was completed using the target word. The sentence frames are classified as low predictability if the target word was rarely used to complete the sentence, and as high predictability if the target word was frequently used to complete the sentence.
and the low predictability sentences had a mean cloze probability of .01 (range = 0 to .08). In addition, to ensure that the local context surrounding the target word was similar in complexity and difficulty across the two sentence versions, an average of 1.4 words immediately before the target and 2.8 words after the target remained constant across the two sentence versions. The mean word length of the target words was 6.25 (range = 4 to 9 letters), and the mean SUBTLex word frequency (Brysbaert & New, 2009) was 66.76 occurrences per million.

Participants read a total of 255 sentences, including 5 practice trials, 80 experimental trials and 170 non-experimental filler sentences that were designed to mask the experiment’s purpose. To provide sufficient power for the distributional analyses, the participants were shown both the high predictability and low predictability versions for all 40 of the sentence pairs. The order of trials was randomized with the constraint that each target word was read once in each half of the experiment, with 75 non-experimental filler trials separating the two halves of the experiment. For each participant, half of the target words appeared in the high predictability sentence first, and half of the target words appeared in the low predictability sentence first, and the order of the two versions of the sentence pairs was counterbalanced across participants. All sentences were displayed on a single line, and the target words were located near the middle of the sentences.

**Apparatus and Procedure**

Eye movements were measured with an SR Research EyeLink 1000 system with high spatial resolution and a sampling rate of 1000 Hz. Following calibration, gaze-position error was less than 0.5°. The sentences were displayed on a 21-in. ViewSonic monitor. All letters were
lowercase (except when capitals were appropriate) and in a mono-spaced Courier font. The text was presented in black \(4.7 \text{ cd/m}^2\) on a white background \(56 \text{ cd/m}^2\). Participants were seated 60 cm from the monitor, and 2.4 characters equaled approximately 1 degree of visual angle. Participants were instructed to read the sentences for comprehension. After reading each sentence, they pressed a button to end the trial and proceed to the next sentence. To ensure that participants were reading for comprehension, about 20% of the sentences were followed by multiple-choice comprehension questions. The average accuracy rate was 97%.

2.2 Results and Discussion

The present study’s main focus was on using a survival analysis technique (Reingold et al., 2012) to study the time course of the predictability variable. However, prior to reporting the survival analysis results, I will first confirm that the present study’s predictability manipulation can replicate past findings by examining standard eye movements measures, as well as the ex-Gaussian parameters that were reported by Staub (2011).

For the analyses reported below, 14.0% of trials were removed due to skipping of the target words. For the remaining trials, the following measures were used to compare mean fixation times on the target words in the high predictability context versus the low predictability context conditions: (a) first-fixation duration (i.e., the duration of the first forward fixation on the target, regardless of the number of subsequent fixations on the target); (b) gaze duration (i.e., the sum of all the consecutive first-pass fixations on the target, prior to a saccade to another word); (c) single-fixation duration (i.e., the first-fixation value for the subset of trials in which there was only one first-pass fixation on the target); (d) go-past time (i.e., the sum of all fixations from the
first fixation on the target up to and including the fixation prior to the reader moving past the
target to a later part of the sentence) (e) the probability of skipping (i.e., trials in which there was
no first-pass fixation on the target regardless of whether or not the target was fixated later in the
trial); and (f) the probability of a single first-pass fixation. For all of these measures, planned
comparisons by participants ($t_1$) and by items ($t_2$) were performed across the two context
conditions. Table 1 presents the means and standard errors of the different measures and the
corresponding $t$ test results.
Table 1

*Average fixation time measures (in milliseconds) and the probability (proportion) of skipping and single fixation by context condition.*

<table>
<thead>
<tr>
<th>Measure</th>
<th>Low Predictability</th>
<th>High Predictability</th>
<th>Difference</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>first-fixation (all trials)</strong></td>
<td>216, 4.3</td>
<td>208, 3.6</td>
<td>8</td>
<td>$t_1 = 3.34, p &lt; .01$ $t_2 = 2.59, p &lt; .05$</td>
</tr>
<tr>
<td><strong>gaze duration (all trials)</strong></td>
<td>243, 6.3</td>
<td>230, 5.2</td>
<td>13</td>
<td>$t_1 = 3.46, p &lt; .01$ $t_2 = 2.63, p &lt; .05$</td>
</tr>
<tr>
<td><strong>single-fixation</strong></td>
<td>218, 4.5</td>
<td>208, 3.8</td>
<td>10</td>
<td>$t_1 = 3.12, p &lt; .01$ $t_2 = 2.67 p &lt; .05$</td>
</tr>
<tr>
<td><strong>go-past time</strong></td>
<td>302, 9.3</td>
<td>274, 8.3</td>
<td>28</td>
<td>$t_1 = 5.01, p &lt; .001$ $t_2 = 3.57, p &lt; .01$</td>
</tr>
<tr>
<td><strong>prob. of skipping</strong></td>
<td>.12, .01</td>
<td>.16, .01</td>
<td>-.04</td>
<td>$t_1 = 3.61, p &lt; .01$ $t_2 = 3.16, p &lt; .01$</td>
</tr>
<tr>
<td><strong>prob. of single fixation</strong></td>
<td>.75, .01</td>
<td>.74, .01</td>
<td>.01</td>
<td>$t_1 = 1.00, p = .319$ $t_2 = 1.00, p = .323$</td>
</tr>
</tbody>
</table>

Note – For the $t$ tests shown above, $df$ for $t_1 = 59$, and $df$ for $t_2 = 39$. The means and standard errors shown are based on the by-participants analyses.

As shown in Table 1, fixation times on the target words were longer for the low predictability context condition relative to the high predictability context condition, and this effect was significant for first-fixation, gaze duration, single-fixation, and go-past time. In addition, the target words were more likely to be skipped in the high predictability condition than in the low predictability condition, but the probability of a single fixation did not differ across
conditions. Overall, this pattern of results replicates a large body of prior work concerning the predictability variable (e.g., Ehrlich & Rayner, 1981; Rayner & Well, 1996; Rayner et al., 2004).

Next, I fitted the ex-Gaussian distribution to the first-fixation duration data using a similar procedure as Staub at al. (2010). The ex-Gaussian distribution (Ratcliff, 1979) is the convolution of the Gaussian normal distribution and an exponential distribution, and can be specified with the following three parameters: $\mu$ (the mean of the Gaussian component), $\sigma$ (the standard deviation of the Gaussian component) and $\tau$ (the mean and the standard deviation of the exponential component). Following Staub at al. (2010), the first-fixation duration data for each participant in each condition were fitted separately, using an algorithm known as quantile maximum likelihood estimation (QMPE; Cousineau, Brown, & Heathcote, 2004; Heathcote, Brown, & Mewhort, 2002). There were an average of 34 usable observations per cell, and all fits successfully converged. Table 2 displays the mean number of usable observations per cell, the means of the $\mu$, $\sigma$, and $\tau$ parameters, and the magnitude and significance of the low vs. high predictability context effects, and Figure 1 displays the distributions of first-fixation durations.

To create Figure 1 (panel a), I separately computed the proportion of first-fixation durations that fell within each successive 25-ms bin over the range from 0 to 600 ms for each participant and each condition, and I then averaged these values across participants. In addition, Figure 1 (panel

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$^3$ The formula for the ex-Gaussian probability density function is:

$$f(x| \mu, \sigma, \tau) = \frac{1}{\tau} \exp \left( \frac{\mu}{\tau} + \frac{\sigma^2}{2\tau^2} - \frac{x}{\tau} \right) \Phi \left( \frac{x - \mu - \sigma^2}{\sigma \tau} \right)$$

In the above equation, the exponential function (exp) is multiplied by the value of the cumulative density of the Gaussian (normal) function symbolized by $\Phi$, and the resulting ex-Gaussian function has three parameters ($\mu$, $\sigma$, and $\tau$). For further details, see e.g., Cousineau et al. (2004), Heathcote et al. (2002), Lacouture and Cousineau (2008), and Ratcliff (1979).
b) displays the density functions that were generated from the best-fitting ex-Gaussian parameters. As shown in Table 2 and Figure 1, the low predictability distribution was shifted to the right of the high predictability distribution, resulting in a significant \( \mu \) effect. There were no significant differences for \( \sigma \) and \( \tau \). This pattern of ex-Gaussian results replicates Staub (2011)’s predictability findings, and stands in contrast to prior findings that word frequency affects both \( \mu \) and \( \tau \) (Reingold et al., 2012; Staub et al., 2010). Thus, predictability effects on mean fixation times primarily reflect a shift in the location of the distributions, whereas word frequency effects reflect both a shift effect and a change in the degree of skew.

Table 2

*Number of observation per cell and ex-Gaussian parameters by condition. Standard errors are shown in parentheses.*

<table>
<thead>
<tr>
<th>Condition</th>
<th>( n )</th>
<th>Mu (( \mu ))</th>
<th>Sigma (( \sigma ))</th>
<th>Tau (( \tau ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Predictability</td>
<td>35 (0.4)</td>
<td>165 (3.4)</td>
<td>37 (2.4)</td>
<td>52 (4.6)</td>
</tr>
<tr>
<td>High Predictability</td>
<td>34 (0.5)</td>
<td>157 (2.9)</td>
<td>38 (2.2)</td>
<td>51 (2.6)</td>
</tr>
<tr>
<td>Difference</td>
<td>1</td>
<td>8</td>
<td>-1</td>
<td>1</td>
</tr>
<tr>
<td>Significance</td>
<td>( t = 3.61, p &lt; .001 )</td>
<td>( t = 2.48, p &lt; .05 )</td>
<td>( t &lt; 1 )</td>
<td>( t &lt; 1 )</td>
</tr>
</tbody>
</table>

Note - For the \( t \) test results shown above, \( df = 59 \)

To extend the above ex-Gaussian findings, I next computed survival curves for first-fixation durations in the low and high predictability conditions, using the same procedure as Reingold et al. (2012). Specifically, for each 1-ms time bin \( t \) (\( t \) was varied from 0 to 600 ms), the percentage of first fixations with a duration greater than \( t \) constituted the percent survival at time
The survival curve was computed separately for each condition and for each participant, and then averaged across participants. As shown in Figure 1 (Panel c), the low and high predictability survival curves appear to diverge. As previously argued by Reingold et al. (2012), this divergence point corresponds by definition to the shortest first-fixation duration value at which the contextual manipulation had a significant impact. To estimate the divergence point, I employed a bootstrap re-sampling procedure (Efron & Tibshirani, 1994). Specifically, on each iteration of this procedure, the set of observations (first-fixation durations) for each participant in each condition was randomly re-sampled with replacement. For each iteration of the bootstrap procedure, an individual participants’ survival curves were then computed and averaged. Next, the value for each 1-ms bin in the high predictability survival curve was subtracted from the corresponding value in the low predictability survival curve. This procedure was repeated 10,000 times, and the obtained differences for each bin were then sorted in order of magnitude. The range between the 5th and the 9,995th value was then defined as the confidence interval of the difference for each bin (given the multiple comparisons performed, this conservative confidence interval was necessary in order to protect against making a Type I error). To compute the divergence point between the low and high predictability survival curves, I identified the time bins for which the low predictability survival rate was significantly greater than the high predictability survival rate (i.e., for which the lower bound of the confidence interval of the difference between the low and high predictability curves was greater than zero). The divergence point was then defined as the earliest significant difference point that was part of a run of five consecutive significant difference points (significant differences between the low and high predictability curves are shown in Panel c of Figure 1 as a row of asterisks above the survival curves).
Figure 1. Distributions of first-fixation duration on target words in the low and high predictability conditions (Panel a), and ex-Gaussian density functions (Panels b), and survival curves (Panel c). The row of asterisks at the top of Panel c indicates the time bins with a significant difference between the low and high predictability curves. See text for further details.
As can be seen in Figure 1 (Panel c), the low and high predictability survival curves significantly diverged at a duration of 140 ms, which is similar to the 145 ms divergence point that was previously obtained for the word frequency variable under normal reading conditions (see Reingold et al., 2012). Furthermore, the divergence point defines the percentage of first fixations with durations that were too short to exhibit an influence of predictability. In the present study, only approximately 10% of first fixations had durations that were shorter than the divergence point, which is once again similar to the prior word frequency findings (Reingold et al., 2012). Thus, the predictability and word frequency variables produce equally fast-acting influences on fixation duration, which is consistent with the finding that both of these variables produce a $\mu$ effect. However, as pointed out by Staub (2011), even though the two effects show a similar early time course, there appears to be some later emerging differences between them, as indicated by the finding of a $\tau$ effect for word frequency but not for predictability.

2.3 General Discussion

The present experiment’s results support an early temporal onset of predictability effects during reading. Specifically, target words were read faster when they were encountered in a predictable context, relative to an unpredictable context, and this effect emerged as early as the first fixation on the target word. In replication of Staub (2011), the distribution of first-fixation durations in the low predictability context was shifted to the right of the high predictability distribution, in the absence of any contextual differences in the degree of skew. Moreover, extending these findings, the present study used a survival analysis (see Reingold et al., 2012) to demonstrate a rapid effect of predictability on fixation times that emerged as early as 140 ms from the start of fixation.
The present experiment’s findings converge with prior results (e.g., Rayner et al., 2003; Reingold et al., 2010; Sereno et al., 2003; Sereno et al., 1998; Staub, 2011; Staub et al., 2010) in supporting an early time course of lexical influences during reading. In particular, the finding that lexical variables can produce a shift in the distributions indicates that both short and long fixations were impacted (Staub et al., 2010), and the present study’s survival analyses coincide with prior work (Reingold et al., 2012) in demonstrating rapid lexical influences on fixation durations. Taken together, such findings are consistent with models of eye-movement control that postulate fast-acting lexical influences on the majority of fixation durations during reading, and are inconsistent with a competing class of models that instead assumes that most fixation durations are exclusively driven by visual/oculomotor factors (see Rayner, 1998, 2009a, for reviews).

An additional implication of the present study’s results concerns the temporal relationship between the predictability and word frequency variables. Specifically, the two variables appear to be temporally overlapping during an early stage of processing, as evidenced by the present study’s predictability divergence point of 140 ms, which is comparable to the word frequency divergence point of 145 ms that was previously reported by Reingold et al., (2012). In addition, due to the temporal constraints inherent to saccadic programming in reading (Sereno & Rayner, 2003), these lexical variables begin to exert their influence even earlier than these divergence points (Reingold et al., 2012). This pattern of survival analysis results is consistent with ERP work that demonstrated both word frequency and context effects during the N1 component, from 132–192 ms poststimulus (Sereno et al., 2003). Moreover, with regards to the ex-Gaussian findings, the survival analysis results are generally consistent with the finding that both of the variables can produce a shift in the location of the distributions. However, as discussed by Staub (2011), the finding that there is a skew effect for word frequency but not for
predictability indicates that there are some temporal differences between the two variables with respect to long fixations.

Given that word frequency effects are considered to be a marker of lexical access (Rayner, 1998), the similar temporal onset of word frequency and predictability effects suggests that contextual predictability influences are rapid enough to impact early lexical processes (see Sereno et al., 2003 for a related discussion). However, temporal overlap is not sufficient evidence that both variables are impacting the same stage or process. In fact, previous studies that manipulated both word frequency and predictability have often shown that the two variables do not interact with each other (e.g., Rayner et al., 2004; Slattery, Staub, & Rayner, 2012). Thus, although distributional analyses have revealed an early time-course for several prominent reading variables, further work is needed to clarify the exact processes and mechanisms that underlie these early effects.
3 Experiment 2

Readers frequently encounter homographs (e.g., *bank*), which have multiple meanings associated with a single orthographic form. Competing models of lexical ambiguity resolution agree that readers use contextual information to determine the relevant meaning of a homograph (e.g., the *money* vs. the *river* meaning of *bank*), but controversy has surrounded the temporal locus of contextual influences. On one side of the debate, the modular or autonomous models (e.g., Fodor, 1983; Forster, 1979) have argued that the preceding context does not influence lexical access. Specifically, all meanings of an ambiguous word are accessed exhaustively, regardless of context, and meaning selection is accomplished at the postlexical integration stage. On the other side of the debate, interactive models (e.g., McClelland & Rumelhart, 1981; Morton, 1969) have argued that context can constrain lexical access such that only the contextually relevant meaning is accessed (i.e., selective access).

Historically, the interactive and modular models were tested empirically using the cross-modal priming task (e.g., Swinney, 1979). In this task, participants listened to a disambiguating context and an ambiguous word, while simultaneously responding to a visual prime word that was either related to the contextually relevant or irrelevant meaning of the ambiguous word. The ambiguous word primed both meanings if the prime was presented immediately after the ambiguous word. However, if the prime was delayed by 200 ms, then only the contextually relevant meaning showed priming. This pattern of results was largely interpreted as supporting the modular view that contextual influences are postlexical (Fodor, 1983; Forster, 1979; but see Lucas, 1999).
However, the introduction of eye tracking to the study of lexical ambiguity resolution by Rayner and Duffy (1986) has led to additional findings that could not be easily explained by either the modular or the interactive models (for a comprehensive review of these findings, see Duffy et al., 2001). Briefly, eye tracking studies have manipulated aspects of both the context and the homographs. A key aspect of the homographs is the relative frequency of the various meanings (i.e., meaning dominance; Hogaboam & Perfetti, 1975). Specifically, eye tracking studies have contrasted balanced homographs, which have two approximately equally common meanings, with biased homographs, which have one highly dominant meaning and one or more subordinate meanings. In addition, the preceding context was constructed to either be neutral (i.e., no disambiguating information precedes the homograph), or to instantiate one (or more) of the homograph’s meanings. In most lexical ambiguity studies, fixation times on homographs were compared to fixation times on unambiguous control words that were embedded in the same sentence frames (e.g., Duffy et al., 1988), although several studies have instead used homographs as their own controls by examining fixation times for the same homographs across different context conditions (Dopkins, Morris, & Rayner, 1992; Rayner, Cook, Juhasz, & Frazier, 2006; Rayner & Frazier, 1989; Sheridan et al., 2009).

Importantly, certain combinations of the meaning dominance and context variables produced longer fixation times on the homographs relative to control words (i.e., ambiguity-related processing delays), even when the homographs and their controls were equated on relevant variables such as word frequency and word length. For example, when the preceding context instantiated the subordinate meaning, fixation times were longer on biased homographs than on control words (Duffy et al., 1988). This effect was later termed the subordinate bias effect (SBE) by Pacht and Rayner, (1993) and has been the focus of extensive empirical and theoretical efforts in the literature (Binder & Rayner, 1999; Binder, 2003; Dopkins et al., 1992;
Consequently, two additional models were proposed to explain the full pattern of eye tracking results: the reordered access model (Duffy et al., 1988) and the integration model (Rayner & Frazier, 1989). Specifically, the reordered access model postulates that lexical access is exhaustive, and the order by which meanings are accessed is determined by both preceding contextual information (i.e., meanings instantiated by the preceding context are accessed faster) and meaning dominance (i.e., more common meanings are accessed faster). When these factors or their interaction cause two or more meanings to become available at approximately the same time, competition between the meanings leads to processing delays. For example, when the preceding context supports the subordinate meaning of a biased homograph, it speeds up access to that meaning and causes the subordinate and dominant meaning to become available within the same time window, resulting in the SBE.
In contrast, the integration model (Rayner & Frazier, 1989) proposes that context does not affect lexical access. Instead, the order by which meanings are accessed is determined exclusively by meaning dominance, and context is postulated to affect a postlexical integration stage by facilitating the integration of contextually relevant meanings. According to the integration model, the SBE occurs because integration of the dominant meaning fails and the processor must wait for the subordinate meaning to become available before integration can proceed.

Although both of the models can explain the bulk of the eye movement findings, including the SBE, the results of several empirical studies (Dopkins et al., 1992; Sereno et al., 2003; Sereno, 1995; Sheridan et al., 2009) and simulations (Duffy et al., 2001; Reichle, Pollatsek, & Rayner, 2007) have favoured the reordered access model. For example, in order to distinguish between the two models, Dopkins et al. (1992) placed biased homographs (e.g., *speaker*) in several different context conditions. In this experiment, the most critical condition for testing the two models was the positive condition, in which the preceding context highlighted semantic features of the subordinate meaning but was still consistent with the dominant meaning (e.g., “Inaudible as a result of the static, the *speaker* was completely rewired by the technician”). The integration model predicts that readers should initially integrate the dominant meaning because the positive context does not rule out the dominant meaning. In contrast, the reordered access model predicts that readers should initially integrate the subordinate meaning because the positive context should “boost” the subordinate meaning such that it could compete with the dominant meaning. The reordered access model’s prediction was supported by Dopkins et al. (1992) and by a related follow-up study by Sheridan et al. (2009). Specifically, Dopkins et al. (1992) contrasted the positive context with a neutral control condition, while Sheridan et al. (2009) contrasted the positive context with a dual-meaning (i.e., pun) control condition that
highlighted semantic features of both the dominant and subordinate meanings without ruling out either meaning. Relative to these control conditions, the positive context produced longer fixation times on the homograph itself while simultaneously producing shorter fixation times in a later disambiguating region that clearly instantiated the subordinate meaning. The reordered access model can explain this pattern of results by assuming that readers in the positive condition successfully integrated the subordinate meaning upon encountering the homograph, and thus did not experience difficulty when they later encountered the disambiguating material.

In addition to the approach used by Dopkins et al. (1992) and Sheridan et al. (2009), another way to distinguish between the models is to test their predictions concerning the time course of contextual influences. Critically, the reordered access model proposes an earlier locus of contextual effects during lexical access than does the integration model, which instead assumes that contextual influences are postlexical. Consistent with the reordered access model, an event-related potentials (ERP) experiment by Sereno et al. (2003) and a simulation by Reichle et al. (2007) have supported an early locus of contextual influences during lexical ambiguity resolution. Furthermore, several lexical ambiguity and eye tracking studies (e.g., Kambe et al., 2001; Rayner et al., 2006; Sheridan et al., 2009) have observed contextual influences on the duration of the very first fixation on the homograph (i.e., first-fixation duration). Such first-fixation findings are consistent with the reordered access model’s assumption that context can influence lexical access. This is because the temporal constraints inherent to saccadic programming in reading (Sereno & Rayner, 2003) necessitate that in order for a variable to affect first-fixation duration, it must exert at least part of its influence very early on during the fixation.

However, while the above first-fixation findings are suggestive of an early locus of contextual influences during lexical access, they are not definitive evidence because it also
possible that the first-fixation effects were driven by a subset of trials with very long fixation times. Consequently, the present study’s goal is to provide more decisive evidence for an early locus of contextual influences during lexical ambiguity resolution. To accomplish this goal, the present study examines distributional analyses of first-fixation times on biased homographs (e.g., “suit”) in a subordinate-instantiating prior context (e.g., “The law firm agreed to represent me in the suit that was filed last week.”) versus a dominant-instantiating prior context (e.g., “I went to the dry cleaners to pick up the suit that I'm wearing to the wedding.”). This contextual manipulation was expected to replicate the SBE, by producing longer fixation times in the subordinate relative to the dominant context. To provide time course information about this effect, I again employed two distributional analysis techniques: ex-Gaussian fitting (e.g., Staub, 2011; Staub, White, Drieghe, Hollway, & Rayner, 2010; White & Staub, 2012; White, Staub, Drieghe, & Liversedge, 2011; White, Warren, Staub, & Reichle, 2011), and a survival analysis technique (Reingold et al., 2012). The present study extends these techniques to the lexical ambiguity literature to help to distinguish between lexical ambiguity models, and more generally, to provide further information about the time course of lexical and contextual influences during reading.

The present study uses ex-Gaussian fitting in order to assess whether the SBE’s impact on mean first-fixation duration stems from a shift in the location of the normal component (i.e., an effect on $\mu$) and/or a change in the degree of skew (i.e., an effect on $\tau$). If the SBE stems from a change in the $\mu$ parameter, then such a finding would be consistent with the reordered access model’s assumption of an early locus of contextual influences because it would indicate that both short and long fixations were impacted by the lexical ambiguity manipulation (Staub et al., 2010). However, if the SBE effect primarily reflects a $\tau$ effect, then such a finding would be
more consistent with the integration model’s assumption of late-acting contextual influences because it would indicate that the contextual manipulation mainly influences long fixations.

In addition to analyzing ex-Gaussian distribution parameters as described above, I also examined survival curves for the dominant and subordinate first-fixation duration distributions. As mentioned previously, survival curve analyses were previously used to demonstrate rapid lexical influences that emerged as early as 145 ms from the start of fixation for the word frequency variable (Reingold et al., 2012), and as early as 140 ms from the start of fixation for the predictability variable (see Experiment 1). Following Reingold et al. (2012), the present study calculates the divergence point for the subordinate and dominant curves in order to provide an estimate of the earliest significant influence of the subordinate versus dominant contextual manipulation. If the subordinate and dominant survival curves show an early divergence point that is comparable to the previous word frequency findings (Reingold et al., 2012), then such a pattern of results would be consistent with the reordered access model’s predictions concerning an early locus of contextual influences. However, if the present findings show a later divergence point, then such a finding would support the integration model’s predictions concerning a postlexical locus of contextual findings. Thus, the present study is designed to provide further time course information about the SBE in order to distinguish between models of lexical ambiguity resolution.
3.1 Method

Participants

All 60 undergraduate students at the University of Toronto who participated were native English speakers and were given either course credit or $10 (Canadian) per hour. All had normal or corrected-to-normal vision.

Materials

As shown in Appendix B, 60 sentence pairs were created such that the preceding context instantiated either the dominant meaning (e.g., “The baker used a large bowl to mix together the dough for the bread.”) or the subordinate meaning (e.g., “The used car salesman asked me to pay him the dough for the car.”) of a biased homograph (e.g., “dough”). To ensure that these sentence pairs were matched for predictability, an independent sample of 20 undergraduate students were given the sentence frames up to but not including the homographs, and they were asked to produce the word that seemed most likely to come next in the sentence. The target homographs were produced 16% of the time for the dominant sentence frames, and 14% of the time for the subordinate sentence frames, but this small numerical difference was not significant ($t < 1$). In addition, to minimize differences in local context across the sentences, at least one word prior to the homograph was the same for both sentences (average = 1.6 words), and at least one word after the homograph was the same (average = 1.8 words). The selection of the 60 noun–noun biased homographs that were included in the sentence pairs was based on the results of norming data collected from an independent sample of 108 participants (minimum number of observations per item = 10). The norming procedure involved the participants’ writing the first word that came to mind in response to a list of homographs and unambiguous filler words. The dominant meaning of the homographs had a probability range of .7–1 and a mean of .89, and the
subordinate meaning had a probability range of 0–.3 and a mean of .11. The mean word length of the homographs was 4.93 (range = 3 to 8 letters), and the mean SUBTLex word frequency was 48.02 occurrences per million (Brysbaert & New, 2009).

Participants read five practice sentences followed by 120 experimental sentences and 80 non-experimental filler sentences that were designed to mask the experiment’s purpose. To provide sufficient power for the distributional analyses, the participants were shown both the dominant and subordinate versions for all 60 of the sentence pairs. The order of trials was randomized with the constraint that each homograph was read once in each half of the experiment, with 50 non-experimental filler trials separating the two halves of the experiment. For each participant, half of the homographs appeared in the dominant sentence first, and half of the homographs appeared in the subordinate sentence first, and the order of the two versions of the sentence pairs was counterbalanced across participants. All sentences were displayed on a single line, and the homographs never occupied the last two word positions of the sentence.

**Apparatus and Procedure**

Eye movements were measured with an SR Research EyeLink 1000 system with high spatial resolution and a sampling rate of 1000 Hz. Following calibration, gaze-position error was less than 0.5º. The sentences were displayed on a 21-in. ViewSonic monitor. All letters were lowercase (except when capitals were appropriate) and in a mono-spaced Courier font. The text was presented in black (4.7 cd/m²) on a white background (56 cd/m²). Participants were seated 60 cm from the monitor, and 2.4 characters equaled approximately 1 degree of visual angle. Participants were instructed to read the sentences for comprehension. After reading each sentence, they pressed a button to end the trial and proceed to the next sentence. To ensure that
participants were reading for comprehension, about 20% of the sentences were followed by multiple-choice comprehension questions. The average accuracy rate was 97%.

### 3.2 Results and Discussion

The main goal of the experiment was to examine the distributions of first-fixation durations on homographs as a function of the type of prior context (subordinate vs. dominant context conditions). In the results section below, I begin by reporting analyses of mean fixation times, and I then report two types of distributional analyses: ex-Gaussian fitting (Staub et al., 2010) and a survival analysis technique (Reingold et al., 2012).

**Analysis of means**

Trials were excluded from the analyses described below due to track losses (less than 0.1% of all trials) and due to skipping of the target homograph (17.3% of all trials). The following measures were used to compare fixation times on the homographs in the dominant context versus the subordinate context conditions: (a) first-fixation duration (i.e., the duration of the first forward fixation on the homograph, regardless of the number of subsequent fixations on the homograph); (b) gaze duration (i.e., the sum of all the consecutive first-pass fixations on the homograph, prior to a saccade to another word); (c) single-fixation duration (i.e., the first-fixation value for the subset of trials in which there was only one first-pass fixation on the homograph); (d) first of multiple first-pass fixations (i.e., the first-fixation duration for the subset of trials in which there was more than one first-pass fixation on the homograph); (e) go-past time (i.e., the sum of all fixations from the first fixation on the homograph up to and including the fixation prior to the reader moving past the homograph to a later part of the sentence); (f) total time (i.e., the sum of all fixations on the homograph); (g) n − 1 fixation (i.e., the duration of the fixation immediately before the first fixation on the homograph); (h) n + 1 fixation (i.e., the
duration of the fixation immediately after the final first-pass fixation on the homograph); (i) the probability of skipping (i.e., trials in which there was no first-pass fixation on the homograph regardless of whether or not the homograph was fixated later in the trial); and (f) the probability of a single first-pass fixation. For all of these measures, planned comparisons by participants ($t_1$) and by items ($t_2$) were performed across the two context conditions. Table 3 presents the means and standard errors of the different measures and the corresponding $t$ test results.
Table 3

*Average fixation time measures (in milliseconds) and the probability (proportion) of skipping and single fixation by context condition.*

<table>
<thead>
<tr>
<th>Measure</th>
<th>Subordinate Context</th>
<th>Dominant Context</th>
<th>Difference</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( M )</td>
<td>( SE )</td>
<td>( M )</td>
<td>( SE )</td>
</tr>
<tr>
<td>first-fixation (all trials)</td>
<td>228</td>
<td>4.0</td>
<td>216</td>
<td>4.1</td>
</tr>
<tr>
<td></td>
<td>( t_1 = 5.88, p &lt; .001 )</td>
<td>( t_2 = 4.16, p &lt; .001 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>gaze duration (all trials)</td>
<td>259</td>
<td>6.5</td>
<td>241</td>
<td>5.8</td>
</tr>
<tr>
<td></td>
<td>( t_1 = 5.51, p &lt; .001 )</td>
<td>( t_2 = 4.64, p &lt; .001 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>single-fixation</td>
<td>229</td>
<td>4.2</td>
<td>217</td>
<td>4.4</td>
</tr>
<tr>
<td></td>
<td>( t_1 = 6.48, p &lt; .001 )</td>
<td>( t_2 = 3.93, p &lt; .001 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>first-fixation (multiple)</td>
<td>230</td>
<td>6.5</td>
<td>212</td>
<td>6.5</td>
</tr>
<tr>
<td></td>
<td>( t_1 = 3.03, p &lt; .01 )</td>
<td>( t_2 = 2.49, p &lt; .05 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>go-past time</td>
<td>341</td>
<td>11.1</td>
<td>305</td>
<td>10.6</td>
</tr>
<tr>
<td></td>
<td>( t_1 = 5.83, p &lt; .001 )</td>
<td>( t_2 = 4.51, p &lt; .001 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>total time</td>
<td>371</td>
<td>13.1</td>
<td>316</td>
<td>11.5</td>
</tr>
<tr>
<td></td>
<td>( t_1 = 9.13, p &lt; .001 )</td>
<td>( t_2 = 6.97, p &lt; .001 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>n – 1 fixation</td>
<td>211</td>
<td>3.7</td>
<td>208</td>
<td>3.8</td>
</tr>
<tr>
<td></td>
<td>( t_1 = 1.91, p = .061 )</td>
<td>( t_2 = 1.51, p = .135 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>n + 1 fixation</td>
<td>235</td>
<td>3.9</td>
<td>229</td>
<td>4.3</td>
</tr>
<tr>
<td></td>
<td>( t_1 = 2.44, p &lt; .05 )</td>
<td>( t_2 = 2.13, p &lt; .05 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>prob. of skipping</td>
<td>.17</td>
<td>.01</td>
<td>.18</td>
<td>.01</td>
</tr>
<tr>
<td></td>
<td>( t_1 = 1.53, p = .132 )</td>
<td>( t_2 = 1.54, p = .128 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>prob. of single fixation</td>
<td>.71</td>
<td>.01</td>
<td>.71</td>
<td>.01</td>
</tr>
<tr>
<td></td>
<td>( t_1 &lt; 1 )</td>
<td>( t_2 &lt; 1 )</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note – For the \( t \) tests shown above, \( df = 59 \). The means and standard errors shown are based on the by-participants analyses.
In replication of the SBE (for a review, see Duffy et al., 2001), fixation times on the homographs were longer for the subordinate context condition relative to the dominant context condition. As shown in Table 3, this effect was significant for first-fixation, gaze duration, single-fixation, first of multiple first-pass fixations, n + 1 fixation, go-past time, and total time), and there were no significant effects for the remaining measures (n – 1 fixation, probability of skipping, probability of a single first-pass fixation). Of particular interest to the present study’s time course predictions, this pattern of results replicates previous demonstrations of significant lexical ambiguity effects on single-fixation and first-fixation durations (e.g., Kambe et al., 2001; Rayner et al., 2006; Sheridan et al., 2009), and extends this finding to the first of multiple first-pass fixations measure (see Reingold et al., 2012; Reingold, Yang, & Rayner, 2010, for similar findings with a word frequency manipulation). Thus, the present demonstration of a significant SBE effect on early fixation time measures is consistent with the reordered access model’s predictions concerning an early locus of contextual influences.

Analyses of distributions

Next I will report on the findings obtained from the analyses of the distribution of first-fixation durations by fitting fixation time data using the ex-Gaussian distribution, as well as by employing a survival analysis technique.

Fitting first-fixation duration with the ex-Gaussian distribution. Figure 2 (Panel a) displays the distributions of first-fixation durations by condition (subordinate vs. dominant). To create this figure, I separately computed the proportion of first-fixation durations that fell within each successive 25-ms bin over the range from 0 to 600 ms for each participant and each condition, and I then averaged these values across participants. As can be seen from Figure 2, distributions of first-fixation durations in reading tend to be approximately normal in shape with
some degree of rightward skew. To further characterize the nature of this distribution, I fitted the ex-Gaussian distribution to the first-fixation data using the procedures described in Experiment 1. First-fixation duration data for each participant in each condition were fitted separately. There were an average of 50 usable observations per cell (see Table 4), and all fits successfully converged. Table 4 displays the mean number of usable observations per cell, the parameter estimates, and the magnitude and significance of the subordinate vs. dominant context effects, and Figure 2 (Panel b) displays the density functions generated from the best-fitting ex-Gaussian parameters averaged across participants.

Table 4

*Number of observation per cell and ex-Gaussian parameters by condition. Standard errors are shown in parentheses.*

<table>
<thead>
<tr>
<th></th>
<th>n</th>
<th>Mu (µ)</th>
<th>Sigma (σ)</th>
<th>Tau (τ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subordinate sentence</td>
<td>50 (0.8)</td>
<td>169 (3.4)</td>
<td>39 (2.0)</td>
<td>59 (3.1)</td>
</tr>
<tr>
<td>Dominant sentence</td>
<td>49 (0.8)</td>
<td>161 (3.0)</td>
<td>39 (1.7)</td>
<td>54 (2.8)</td>
</tr>
<tr>
<td>Difference</td>
<td>1</td>
<td>8</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>Significance</td>
<td>t = 1.55, p = .127</td>
<td>t = 2.71, p &lt; .01</td>
<td>t &lt; 1</td>
<td>t = 1.51, p = .136</td>
</tr>
</tbody>
</table>

Note – For the t test results shown above, df = 59.
As shown in Table 4 and Figure 2, the subordinate distribution was shifted to the right of the dominant distribution, resulting in a significant $\mu$ effect. There were no significant differences for $\sigma$. There was a small numerical difference (subordinate > dominant) for $\tau$, but this effect was not significant. This pattern of ex-Gaussian results supports the reordered access model’s predictions concerning an early time course of contextual influences, because the presence of a shift in the distributions (i.e., the $\mu$ effect) indicates that the bulk of the fixations were influenced by the contextual manipulation, regardless of their duration. More generally, the present study’s $\mu$ effect is consistent with similar findings that were produced by manipulations of other lexical variables including word frequency (Reingold et al., 2012; Staub et al., 2010), and predictability or contextual constraints (Staub, 2011).

**Survival Analysis.** I computed survival curves for first-fixation durations in the subordinate and dominant context conditions, using the same procedure as described in Experiment 1. Specifically, for each 1-ms time bin $t$ ($t$ was varied from 0 to 600 ms), the percentage of first fixations with a duration greater than $t$ constituted the percent survival at time $t$. The survival curve was computed separately for each condition and for each participant, and then averaged across participants. As shown in Figure 2 (Panel c), the subordinate and dominant survival curves appear to diverge. Importantly, this divergence point corresponds by definition to the shortest first-fixation duration value at which the contextual manipulation had a significant impact. To estimate the divergence point, I used the same bootstrap re-sampling procedure (Efron & Tibshirani, 1994) that was employed in Experiment 1. Significant differences between the subordinate and dominant curves are shown in Panel c of Figure 2 as a row of asterisks above the survival curves).
Figure 2. Distributions of first-fixation duration on homographs in the subordinate and dominant conditions (Panel a), and ex-Gaussian density functions (Panels b), and survival curves (Panel c). The row of asterisks at the top of Panel c indicates the time bins with a significant difference between the subordinate and dominant curves. See text for further details.
As can be seen in Figure 2 (Panel c), the dominant and subordinate survival curves significantly diverged at a duration of 139 ms, which is similar in duration to the divergence points that were previously obtained for the word frequency variable (see Reingold et al., 2012), and for the predictability variable (see Experiment 1). Furthermore, the divergence point defines the percentage of first fixations with durations that were too short to exhibit an influence of lexical ambiguity. In the present study, only approximately 8% of first fixations had durations that were shorter than the divergence point, which is once again similar to the prior word frequency findings (Reingold et al., 2012). Given that word frequency effects are often used as an empirical marker of lexical processing (see Rayner, 1998, 2009a), the fact that the present study’s temporal estimates are equally as rapid as the word frequency estimates provides strong evidence for an early locus of contextual influences during lexical ambiguity resolution. Taken together, the ex-Gaussian and survival analysis results are consistent with the reordered access model’s assumption that contextual influences can impact lexical access, and are difficulty to reconcile with the integration model’s assumption that contextual influences are postlexical.

3.3 General Discussion

The present findings provide strong support for an early locus of contextual influences during lexical ambiguity resolution. Specifically, to provide fine-grained time course information, the present study examined both mean and distributional analyses of fixation times on homographs in a dominant-instantiating versus a subordinate-instantiating context condition. This contextual manipulation replicated the SBE (for a review see Duffy et al., 2001) by producing longer mean fixation times on the subordinate than the dominant condition across a variety of early fixation duration measures, including first-fixation, single-fixation, and first in
multiple first-pass fixations. Furthermore, the distributional analyses supported an early time course of contextual influences. In particular, the ex-Guassian analysis revealed that the subordinate distribution was shifted to the right of the dominant distribution (i.e., a significant $\mu$ effect), and the survival analysis revealed that an effect of the contextual manipulation on first-fixation duration was evident as early as 139 ms from the start of the fixation.

Consistent with the present findings, ERP work has demonstrated rapid contextual influences on the N1 component (132–192 ms post-stimulus onset) during lexical ambiguity resolution (Sereno et al., 2003). Moreover, several previous lexical ambiguity studies have shown contextual effects on the duration of the first fixation on the homograph (e.g., Kambe et al., 2001; Rayner et al., 2006; Sheridan et al., 2009), and the SBE has been demonstrated using a single adjective immediately preceding the homograph (e.g., “table”), such that fixation times on the homograph were longer following a subordinate-instantiating (e.g., “statistical table”) relative to a dominant-instantiating (e.g., “kitchen table”) prior context (Rayner et al., 2006). Consistent with these empirical findings, a simulation by Reichle et al. (2007) incorporated the assumption that contextual influences during lexical ambiguity resolution are rapid enough to influence the earliest stage of lexical processing (i.e., the L1 stage in the E-Z Reader model; Reichle, Warren, & McConnell, 2009; Reichle, Pollatsek, Fisher, & Rayner, 1998).

Of relevance to contemporary theories of lexical ambiguity resolution, rapid contextual influences are consistent with the reordered access model’s assumption that context can influence lexical access, and are inconsistent with the integration model’s assumption that context does not play a role until the postlexical integration stage. More specifically, to explain the SBE, the reordered access model (Duffy et al., 1988) assumes that a subordinate-instantiating context can influence lexical access by speeding up the access of the subordinate meaning such
that it can compete with the dominant meaning. In marked contrast, the integration model (Rayner & Frazier, 1989) contends that the SBE stems from processing difficulty during the postlexical integration stage. According to the integration model, the SBE occurs because readers fail to integrate the dominant meaning, and must then wait for the subordinate meaning to become available in order for integration to proceed. To explain why the SBE emerges as early as the first fixation on the homograph, the integration model could contend that such effects were driven by a small subset of trials with fixation durations that were long enough to enable integration processes to play a role. However, this explanation is inconsistent with the present study’s distributional analyses, because both the ex-Gaussian and the survival analyses demonstrated contextual influences on the vast majority of fixations. Consequently, the present study’s results add to a growing body of evidence that supports the reordered access model (Dopkins et al., 1992; Duffy et al., 2001; Reichle et al., 2007; Sereno et al., 2003; Sereno, 1995; Sheridan et al., 2009).

More generally, lexical ambiguity research has historically played a prominent role in the larger debate over whether lexical access is influenced by context influences (i.e., the interactive perspective; McClelland & Rumelhart, 1981; Morton, 1969) versus impervious to contextual influences (i.e., the modular perspective; Fodor, 1983; Forster, 1979). Similar to previous work on this topic (e.g., Sereno et al., 2003), the present study’s results favour the interactive perspective. However, the present study’s results do not adjudicate between strong interactive accounts that assume that context can lead to selective access of the contextually relevant meaning (e.g., Kellas & Vu, 1999; Vu & Kellas, 1999) and hybrid accounts, such as the reordered access model (Duffy et al., 1988), which instead assumes that context can “reorder” lexical access by speeding the access of the contextually relevant meaning without producing selective access. Rather, the present study’s results support the interactive perspective more
generally by demonstrating that the subordinate vs. dominant contextual manipulation can produce a fast-acting influence on fixation durations.

In addition, the present findings are relevant to ongoing debates over competing models of eye movement control during reading. In this controversy, one class of models assumes that fixation times are primarily driven by visual/oculomotor factors and that lexical variables can only impact a small subset of long fixations, whereas a competing class of models assumes that lexical variables can have a fast-acting influence on the majority of fixation times during reading (see Rayner, 1998, 2009a, for reviews). In support of the latter class of models, the present study’s results coincide with previous findings that lexical variables in reading are fast-acting. Such findings include the dramatic demonstration that word frequency effects still occur even when the text disappears 60 ms into the fixation (Rayner et al., 2003), and the finding that a wide range of lexical variables can impact first-fixation duration, including lexical ambiguity (see Duffy et al., 2001 for a review), word frequency (see White, 2008, for a review), predictability or contextual constraint (e.g., Ehrlich & Rayner, 1981; Staub, 2011; Experiment 1), and age of acquisition (e.g., Juhasz & Rayner, 2006). More recently, ex-Gaussian analyses have shown that lexical variables can produce shifts in distributions of fixation durations, which indicates that they are impacting the majority of fixations, regardless of duration. For example, the present study’s lexical ambiguity manipulation produced a shift in first-fixation durations, and prior work has shown a similar shift effect for word frequency (Reingold et al., 2012; Staub et al., 2010) and predictability (Staub, 2011). Finally, survival curve analyses have produced rapid temporal estimates of the earliest impact of lexical variables on fixation times, both in the present study and in prior work concerning word frequency (Reingold et al., 2012). Taken together, these findings support models of eye-movement control that postulate fast-acting direct lexical control of fixation times during reading (see Rayner, 1998, 2009a, for reviews).
In sum, the present study provided strong support for a rapid time course of contextual influences during lexical ambiguity resolution. This pattern of results fits well with the time course predictions of the reordered access model and is inconsistent with the integration model. Moreover, of relevance to models of eye movement control, the present study’s results provide convergent evidence for an early time course of lexical influences during reading. Finally, the present study demonstrates that distributional analysis techniques can provide a useful method for studying the time course of lexical ambiguity effects. Future research could further employ these techniques to examine the time course of other types of ambiguity effects (e.g., syntactic ambiguity, garden path sentences, etc.).

4 Experiments 3A and 3B

What is the role of interword spaces during reading? Past studies have addressed this question by examining reading performance for text without spaces (i.e., unsegmented text). Removing spaces in English produces longer fixation durations and reduced reading rates (e.g., Malt & Seamon, 1978; Morris, Rayner, & Pollatsek, 1990; Perea & Acha, 2009; Pollatsek & Rayner, 1982; Rayner, Fischer, & Pollatsek, 1998; Spragins, Lefton, & Fisher, 1976; Yang & McConkie, 2001). For example, relative to normal text, there is a 30-50% decrement in reading rates when spaces are either removed entirely, or replaced with various types of filler characters, such as letters, digits, or bloblike gratings (Rayner et al., 1998). Moreover, investigations of languages that naturally do not contain spaces (e.g., Japanese, Chinese, Thai) have typically shown that adding interword spaces does not harm reading performance, and sometimes even improves performance (e.g., Bai, Yan, Liversedge, Zang, & Rayner, 2008; Sainio, Hyönä,
Bingushi, & Bertram, 2007; Shen et al., 2012; Winskel, Perea, & Ratitamkul, 2012; Winskel, Radach, & Luksaneeyanawin, 2009). Taken together, these findings highlight the importance of spaces during reading. Although readers can still comprehend unsegmented text (Epelboim, Booth, & Steinman, 1994), they consistently show dramatic decreases in reading efficiency when spaces are removed (Rayner et al., 1998).

To explain the disruption caused by unsegmented text, Rayner et al. (1998) proposed that unsegmented text separately interferes with both saccadic programming and word identification processes. Specifically, spaces facilitate saccadic programming by providing visual cues concerning word boundaries and word length. Thus, whereas normal text produces initial landing positions that are close to the centre of the word (i.e., the preferred viewing position, PVP; Rayner, 1979), unsegmented text disrupts saccadic programming such that initial landing locations are shifted closer to the beginning of the word (e.g., Paterson & Jordan, 2010; Perea & Acha, 2009; Rayner et al., 1998), and saccade amplitudes are shorter (Paterson & Jordan, 2010; Perea & Acha, 2009; Rayner et al., 1998; Yang & McConkie, 2001).

In addition to facilitating saccadic programming, spaces may also enhance word identification processes, either by facilitating word segmentation by demarcating which characters belong in a word (e.g., Li, Rayner, & Cave, 2009), or by reducing lateral masking (Bouma, 1973; Townsend, Taylor, & Brown, 1971). Consistent with this idea, several researchers have advanced the hypothesis that unsegmented text slows down reading because removing spaces disrupts word identification (Epelboim et al., 1994; Epelboim, Booth, & Steinman, 1996; Morris et al., 1990; Pollatsek & Rayner, 1982; Rayner et al., 1998). To test this hypothesis, Rayner et al. (1998) manipulated word frequency for target words that were imbedded in both normal and unsegmented sentences, in order to test for interactions between
word frequency (high, low) and text condition (normal, unsegmented). It is well-established that fixation times during reading are longer for low frequency than for high frequency words (Inhoff & Rayner, 1986; Rayner & Duffy, 1986; see White, 2008 for a review), and such word frequency effects are considered to be a temporal marker of lexical processing (Rayner, 1998; Reingold et al., 2012). Rayner et al. (1998) observed that unsegmented text increases the magnitude of word frequency effects relative to normal text (for similar findings, see Paterson & Jordan, 2010; Perea & Acha, 2009), and they interpreted this interaction as evidence that unsegmented text disrupts word identification rather than interfering only with a more superficial level of visual processing (for a similar logic, see Booth, Epelboim, & Steinman, 1995; Sternberg, 1969).

Building on the above findings, the goal of the present study was to provide fine-grained evidence concerning the extent to which removing spaces delays word identification. To accomplish this goal, I employed several distributional analysis techniques that have recently proven useful for examining the time course of the influence of different variables during reading (e.g., Reingold et al., 2012; Staub, 2011; Staub, White, Drieghe, Hollway, & Rayner, 2010; White & Staub, 2012; White, Staub, Drieghe, & Liversedge, 2011; White, Warren, Staub, & Reichle, 2011). In particular, I used a survival analysis technique (Reingold et al., 2012), and ex-Gaussian fitting (Staub et al., 2010) to compare the time course of word frequency effects under normal versus unsegmented text conditions.

Accordingly, I presented both high and low frequency target words in a normal text condition that contained spaces (e.g., “John decided to sell the table in the garage sale”) and in an unsegmented text condition that contained random numbers instead of spaces (e.g., “John4decided8to5sell9the7table2in3the9garage6sale”). I selected random numbers as fillers because I expected them to be less predictable and thus more disruptive than uniform fillers, such
as the letter ‘x’ filler that was employed by Rayner et al. (1998). Using the survival analysis and ex-Gaussian techniques described previously, I then tested for a delayed temporal onset of word frequency effects in the unsegmented relative to the normal text condition. On the premise that word frequency effects are a temporal marker of lexical processing (Reingold et al. 2012; Rayner, 1998, 2009a), such a delay would support the hypothesis that unsegmented text slows down word identification.

In the two proceeding chapters, equally rapid divergence points were shown for the predictability variable (see Experiment 1), and the lexical ambiguity variable (see Experiment 2). In the present experiment, I examined whether the normal versus unsegmented text manipulation impacts the location of the divergence point between the high and low frequency survival curves. If the unsegmented text condition produces a later divergence point relative to the normal text condition, then such a pattern of results would indicate that removing spaces delays word identification. However, if the normal and unsegmented text conditions produce equivalent divergence points, then such a pattern of results would indicate that removing spaces does not slow down lexical processing.

In addition to examining survival curves, I employed ex-Gaussian fitting (Staub et al., 2010) to model individual participants’ distributions of fixation times during reading. A key advantage of ex-Gaussian fitting is that it clarifies whether a variable’s impact on mean fixation times is due to a shift in the location of the distribution and/or a change in the degree of skew. As explained by Staub et al. (2010), a shift effect indicates that the variable is having an early acting influence on the majority of fixation durations, whereas a skew effect primarily stems from an influence on long fixation durations. Under normal reading conditions, the word frequency variable produces both a shift effect and a skew effect (Reingold et al., 2012; Staub et al., 2010).
In the present study, I examined if this pattern of results could extend to the unsegmented text condition. In particular, given the hypothesis that word identification is slower for unsegmented text, I was interested in testing if the word frequency variable would still be fast acting enough to produce a shift effect for the unsegmented text condition.

Thus, the main goal of the present experiment was to employ distributional analyses to compare the time course of word frequency effects under both normal and unsegmented text conditions. However, as an additional question of interest, I also contrasted the pattern of results when text condition (normal, unsegmented) was manipulated within subject (Experiment 3A) versus between subjects (Experiment 3B). These two types of manipulations were included to confirm that the pattern of distributional results could replicate across a variety of experimental contexts. To the extent that the disruption caused by unsegmented text is due to low-level visual factors (e.g., lateral masking) rather than higher level strategic influences, it is possible that the within versus between-subjects manipulation will not influence the qualitative pattern of results. However, I speculated that overall levels of reading performance might differ across the within-subject manipulation and between-subjects manipulation, because it has been previously shown that single word reading performance differs for items presented in “pure” blocks that contain a single type of trial, relative to “mixed” blocks that contain more than one type of trial (Lupker, Brown, & Colombo, 1997; Monsell, Patterson, Graham, Hughes, & Milroy, 1992; Rastle, Kinoshita, Lupker, & Coltheart, 2003). Given that previous studies have primarily used within-subject manipulations to contrast normal and unsegmented text (e.g., Rayner et al., 1998), I wished to explore the ramifications of using a within versus a between-subjects design.
4.1 Method

Participants

All 248 participants (104 in Experiment 3A and 144 in Experiment 3B) were undergraduate students at the University of Toronto. The participants were all native English speakers and were given either one course credit, or $10.00 (Canadian) per hour. All participants had normal or corrected to normal vision.

Materials and Design

In both Experiments 3A and 3B, the target words consisted of 120 low frequency nouns and 120 high frequency nouns, which ranged in word length from 5 to 10 letters ($M = 6.5$). The mean word frequency was 2.5 occurrences per million for the low frequency targets, and 112.1 occurrences per million for the high frequency targets, according to the SUBTLex corpus of American English subtitles (Brysbaert & New, 2009). I then created 120 pairs of high and low frequency words (matched on word length), and two low-constraint sentence frames were composed for each of these word pairs so that either word could plausibly fit into the sentences (see Appendix C for the complete list of sentences). For example, sentences 1A and 1B below were created for the pair of words, table and banjo:

1A) John decided to sell the table/banjo in the garage sale.

1B) I was told that the table/banjo was made out of expensive wood.

Target word predictability in these sentence frames was assessed by providing an additional group of 10 participants with the beginning of each sentence frame and asking them to write a word that could fit as the next word in the sentence. Average predictability was
extremely low, amounting to 1.3% for the high-frequency target words and 0.1% for low-frequency target words.

In addition to the frequency manipulation, both Experiments 3A and 3B contrasted a normal text condition with an unsegmented text condition that contained random numbers between 2 and 9 instead of spaces (e.g., John4decided8to5sell9the7table2in3the9garage6sale). Thus, four experimental conditions resulted from crossing frequency (high vs. low) and text condition (normal vs. unsegmented). The word frequency variable was manipulated within subject for both Experiments 3A and 3B, and text condition was manipulated within subject for Experiment 3A (i.e., all 104 participants read a mixture of normal and unsegmented text trials), and as a between-subjects manipulation for Experiment 3B (i.e., 72 of the participants only read the normal text condition, and the remaining 72 participants only read the unsegmented text condition). In Experiment 3A, participants read 16 practice trials followed by 240 experimental trials and 40 filler trials. In Experiment 3B, the practice trials (5 practice trials in the normal text condition, and 16 practice trials in the unsegmented text condition), were followed by 120 experimental trials and 160 filler trials. Thus, in both Experiments 3A and 3B, the participants read a total of 280 sentences plus practice trials. The experimental and filler sentences were presented in a random order, and each participant read any given target word or sentence frame only once. The assignment of target words to sentence frames and conditions was always counterbalanced across participants.

**Apparatus and Procedure.**

Eye movements were measured with an SR Research EyeLink 1000 system with high spatial resolution and a sampling rate of 1000 Hz. Viewing was binocular, but only the right eye was monitored. A chin rest and forehead rest were used to minimize head movements. Following
calibration, gaze-position error was less than 0.5°. The sentences were displayed on a 21 in. ViewSonic monitor with a refresh rate of 150 Hz and a screen resolution of 1024 × 768 pixels. All letters were lowercase (except when capitals were appropriate). The text was presented in black (4.7 cd/m$^2$) on a white background (56 cd/m$^2$). Participants were seated 60 cm from the monitor, and 2.4 characters equaled approximately 1 degree of visual angle. All sentences were displayed on a single line, and the target words were located near the middle of the sentences. The average number of words in each sentence was 11.2 words (range = 6 to 16 words).

Prior to the experiment, all of the participants were told to focus on reading the sentences for comprehension. In addition, for Experiment 3A, and for Experiment 3B’s unsegmented text condition, the participants were informed that they would encounter sentences that contained numbers instead of spaces. After reading each sentence, participants pressed a button to end the trial and proceed to the next sentence. To ensure that participants were reading for comprehension, about 15% of the sentences were followed by multiple-choice comprehension questions. The average accuracy rate was above 90% for both experiments (3A, 3B) and for both text conditions (normal, unsegmented).

4.2 Results

My main goal was to employ the ex-Gaussian and survival analysis techniques to examine the time course of word frequency effects in the unsegmented versus the normal text conditions. However, prior to reporting the distributional analyses, I first confirmed that I could replicate past findings by examining landing positions and a variety of standard global and target region measures. For the global analyses, trials were excluded due to data losses (less than 1% of trials), and the first and last fixations in a trial were always excluded. For the analysis of landing
positions and the target region analyses, trials were excluded due to data losses (less than 1% of trials), and due to skipping of the target (3% to 11% of trials). 4

**Analysis of landing positions**

I examined the impact of text condition (normal, unsegmented) on initial landing positions on the high and low frequency target words. Specifically, for each target word, I defined a target region from the middle of the space prior to this word to the middle of the space following this word. To obtain the measure of landing position, I then calculated the proportion of the target region that was to the left of the position of the first fixation on the target region (for a more detailed description of this measure, see Reingold et al., 2012). For each experiment, 2 x 2 analyses of variance (ANOVA)s were carried out on the landing position data via both participants ($F_1$) and items ($F_2$), with text condition (normal, unsegmented) and word frequency (high, low) as independent variables. Figure 3 displays the distribution of landing positions for each condition and for each experiment. To create this figure, I divided the target region into 5 equally spaced landing location bins (i.e., each bin contained 20% of the target region), and then calculated the proportion of fixations per bin. As can be seen from Figure 3, landing positions were closer to the beginning of the word for the unsegmented condition relative to the normal condition (all $F$s $> 18$, all $p$s $< .001$), and the average size of this shift corresponded to a distance of .43 character spaces in Experiment 3A and .42 character spaces in Experiment 3B. This shift

4 The location and target region analyses were also conducted using outlier rejection cut-off points. Specifically, in these analyses, I excluded all trials in which the first fixation on the target was below 80 ms or above 1000 ms. The percentage of outlier trials was extremely small (i.e., 1.7% for the normal condition and 1.4% for the unsegmented condition in Experiment 3A, and 1.2% for the normal condition and 0.9% for the unsegmented condition in Experiment 3B). Since the exclusion of these outlier trials did not affect the pattern of results, I report the results without outlier rejection in the main text.
in the distribution of landing positions replicates past findings (e.g., Paterson & Jordan, 2010; Perea & Acha, 2009; Rayner et al., 1998), and suggests that unsegmented text interferes with saccadic programming. In addition, landing positions were shifted closer to the beginning of the word for low frequency relative to high frequency words (by an average of .07 character spaces in both experiments), and this word frequency effect was significant in Experiment 3A (all $F$s > 8, all $p$s < .01), and in Experiment 3B for the by-items analysis ($F_{2[1,119]} = 4.28, p < .05$) but not for the by-participants analysis ($F_{1[1,142]} = 3.47, p = .065$). This word frequency effect might have stemmed from differences in orthographic familiarity across the high and low frequency words in this experiment. I did not control for orthographic familiarity which has been previously shown to impact landing positions on target words (e.g., Plummer & Rayner, 2012; White & Liversedge, 2004). There were no significant interactions between word frequency and text condition (all $F$s < 4, all $p$s > .05).
Figure 3. The distribution of initial landing positions by word frequency condition (high, low) and text condition (normal, unsegmented), in Experiment 3A (Panel a) and Experiment 3B (Panel b). To create this figure, the target word region was divided into five equally spaced landing position bins, and I then calculated the proportion of fixations per bin (see text for details).
Analysis of global and target region measures

For each of the global and target region measures reported below, two types of 2 x 2 analyses of variance (ANOVA) were carried out on the data via both participants ($F_1$) and items ($F_2$). The first type of analysis examined the influence of text condition (unsegmented, normal) and word frequency (high, low) separately for each of the two experiments (3A, 3B). The second type of analysis was designed to contrast performance across the two experiments by examining the influence of Experiment (3A, 3B) and word frequency (high, low), separately for each of the two text conditions (normal, unsegmented).

For the global analyses, I calculated the average reading rate, fixation duration, number of fixations per sentence, forward saccade size, and the number of saccades per sentence. Table 5 summarizes the means and standard errors for these global measures. Within both experiments, there was less efficient reading performance (i.e., decrements in reading rates, longer fixation durations, shorter forward saccades, and an increase in the number of fixations and saccades per sentence) in the unsegmented condition relative to the normal condition (all $F$s > 20 all $p$s < .001), and in the low frequency condition relative to the high frequency condition (all $F$s > 14 all $p$s < .001). There were typically no significant interactions between text condition and word frequency (all $F$s < 4 all $p$s > .06), with the exception that the forward saccade size measure showed a significant interaction in Experiment 3B (but not in Experiment 3A), such that there was a significantly larger word frequency effect on forward saccade size in the unsegmented

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5 Although the word frequency effects for the global measures were small in magnitude (see Table 5), they were nonetheless significant. These effects were likely driven by differences in the processing of the target words rather than from global differences in the processing of the entire sentence.
condition relative to the normal condition (all $F$s > 4, all $p$s < .05). When performance was contrasted across the two experiments, both the normal and unsegmented conditions showed a numerical trend towards less efficient reading performance in Experiment 3B relative to 3A. For all of the global measures, this numerical trend was significant by items (all $F$s > 15 all $p$s < .001) but not by participants (all $F$s < 4 all $p$s > .06), and there was also an effect of word frequency (all $F$s > 10 all $p$s < .01) that did not interact with the Experiment variable (all $F$s < 3 all $p$s > .09).
<table>
<thead>
<tr>
<th>Measure</th>
<th>Normal text</th>
<th>Unsegmented text</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>High Frequency</td>
<td>Low Frequency</td>
</tr>
<tr>
<td>Reading rate (words/min)</td>
<td>274 7.6</td>
<td>261 7.6</td>
</tr>
<tr>
<td>Fixation duration (ms)</td>
<td>200 2.4</td>
<td>203 2.4</td>
</tr>
<tr>
<td>Number of fixations per sentence</td>
<td>10.5 0.29</td>
<td>11.1 0.32</td>
</tr>
<tr>
<td>Forward saccade size (degrees of visual angle)</td>
<td>3.3 0.07</td>
<td>3.3 0.07</td>
</tr>
<tr>
<td>Number of saccades per sentence</td>
<td>11.3 0.29</td>
<td>11.9 0.32</td>
</tr>
</tbody>
</table>

Experiment 3A (within-subject manipulation)

Experiment 3B (between-subjects manipulation)

<table>
<thead>
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<th>Unsegmented text</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>High Frequency</td>
<td>Low Frequency</td>
</tr>
<tr>
<td>Reading rate (words/min)</td>
<td>267 9.1</td>
<td>259 9.2</td>
</tr>
<tr>
<td>Fixation duration (ms)</td>
<td>208 3.2</td>
<td>210 3.1</td>
</tr>
<tr>
<td>Number of fixations per sentence</td>
<td>10.1 0.31</td>
<td>10.6 0.34</td>
</tr>
<tr>
<td>Forward saccade size (degrees of visual angle)</td>
<td>3.2 0.08</td>
<td>3.2 0.08</td>
</tr>
<tr>
<td>Number of saccades per sentence</td>
<td>11.0 0.31</td>
<td>11.4 0.33</td>
</tr>
</tbody>
</table>

Note - The means and standard errors shown in the table are based on the by-participant analyses.
For the target region analyses, I calculated the following measures: (1) first-fixation duration (i.e., the duration of the first forward fixation on the target, regardless of the number of subsequent fixations on the target); (2) single-fixation duration (i.e., the first-fixation value for the subset of trials in which there was only one first-pass fixation on the target); (3) gaze duration (i.e., the sum of all the consecutive first-pass fixations on the target, prior to a saccade to another word); (4) total time (i.e., the sum of all fixations on the target); (5) the probability of skipping (i.e., trials in which there was no first-pass fixation on the target regardless of whether or not the target was fixated later in the trial); and (6) the probability of a single first-pass fixation. Table 6 summarizes the means and standard errors for these target region measures.

Within both experiments, there were longer fixation times, lower skipping rates, and lower probabilities of a single fixation for the unsegmented condition relative to the normal condition (all $F_s > 20$ all $p_s < .001$), and for the low frequency condition relative to the high frequency condition (all $F_s > 40$ all $p_s < .001$). For the first-fixation and single fixation measures, word frequency effects were equal in magnitude across the normal and unsegmented conditions as indicated by a lack of interactions (all $F_s < 2$ all $p_s > .1$). However, in replication of Rayner et al. (1998), the remaining measures (i.e., gaze duration, total time, probability of skipping, probability of single fixation) produced larger word frequency effects in the unsegmented condition than in the normal condition, and this interaction was significant in both experiments for gaze duration, total time, and probability of skipping (all $F_s > 13$, all $p_s < .001$). For the probability of a single fixation measure, the interactions were significant for Experiment 3A (all $F_s > 13$, all $p_s < .001$), but not for Experiment 3B (all $F_s < 3$, all $p_s > .1$). As previously argued by Rayner et al. (1998), these interactions between word frequency and text condition indicate that unsegmented text interferes with the word identification stage of reading.
When the target region measures were compared across the two experiments, fixation times were longer in Experiment 3B than in Experiment 3A. For the by-participant analyses, this effect was significant for the early fixation time measures (i.e., first-fixation, single-fixation) in the normal condition (all $F$s > 3, all $p$s < .05) but not in the unsegmented condition (all $F$s < 1), and none of the gaze duration and total time by-participant analyses were significant (all $F$s < 4, all $p$s > .06). However, the by-item analyses were significant for all of the fixation time analyses and conditions (all $F$s > 7 all $p$s < .01), except for the gaze duration measure in the unsegmented text condition ($F_{2[1, 119]} = 1.63, p = .204$). There were no differences between the skipping rates across experiments (all $F$s < 2, all $p$s > .2), but there was a numerical trend towards lower probabilities of a single fixation in Experiment 3A than in 3B that was significant for the by-items analysis in the normal condition ($F_{2[1, 119]} = 14.15, p < .001$) but not in the unsegmented condition ($F_{2} < 1$) and not for the by-participant analyses (all $F$s < 3, all $p$s > .09). Finally, there was a significant word frequency effect (all $F$s > 20, all $p$s < .001), which did not show any significant interactions with Experiment (all $F$s < 4, all $p$s > .05).
Table 6

*Target region reading measures by text condition (normal vs. segmented), word frequency condition (high vs. low frequency), and Experiment (3A, 3B).*

<table>
<thead>
<tr>
<th>Measure</th>
<th>Normal text</th>
<th></th>
<th>Unsegmented text</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>High Frequency</td>
<td>Low Frequency</td>
<td>High Frequency</td>
</tr>
<tr>
<td></td>
<td>( M )</td>
<td>( SE )</td>
<td>( M )</td>
<td>( SE )</td>
</tr>
<tr>
<td>First-fixation (ms)</td>
<td>203</td>
<td>2.6</td>
<td>223</td>
<td>2.7</td>
</tr>
<tr>
<td>Single-fixation (ms)</td>
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<td>2.9</td>
<td>228</td>
<td>3.2</td>
</tr>
<tr>
<td>Gaze Duration (ms)</td>
<td>231</td>
<td>4.1</td>
<td>281</td>
<td>6.7</td>
</tr>
<tr>
<td>Total time (ms)</td>
<td>299</td>
<td>6.5</td>
<td>391</td>
<td>11.9</td>
</tr>
<tr>
<td>Probability of skipping</td>
<td>.11</td>
<td>.01</td>
<td>.08</td>
<td>.01</td>
</tr>
<tr>
<td>Probability of single fixation</td>
<td>.75</td>
<td>.01</td>
<td>.69</td>
<td>.01</td>
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<tr>
<td></td>
<td>Experiment 3B (between-subjects manipulation)</td>
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</tr>
<tr>
<td>First-fixation (ms)</td>
<td>213</td>
<td>3.4</td>
<td>232</td>
<td>4.2</td>
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<td>Single-fixation (ms)</td>
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<td>Gaze Duration (ms)</td>
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<td>5.2</td>
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<td>9.6</td>
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<tr>
<td>Total time (ms)</td>
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<td>17.0</td>
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<td>prob. of skipping</td>
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<td>prob. of single fixation</td>
<td>.73</td>
<td>.01</td>
<td>.66</td>
<td>.01</td>
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</table>

Note – The means and standard errors shown in the table are based on the by-participant analyses.
In sum, the global and the target region mean analyses replicated past findings that removing spaces reduces reading efficiency (e.g., Malt & Seamon, 1978; Morris et al., 1990; Perea & Acha, 2009; Pollatsek & Rayner, 1982; Rayner et al., 1998; Spragins et al., 1976; Yang & McConkie, 2001). In addition, both the normal and unsegmented conditions produced robust word frequency effects (Inhoff & Rayner, 1986; Rayner & Duffy, 1986; White, 2008), and there was some evidence that reading efficiency was reduced for Experiment 3B relative to Experiment 3A.

**Analyses of distributions**

Next, I report on the findings obtained from the analyses of the distribution of first-fixation duration by fitting fixation time data using the ex-Gaussian distribution, as well as by employing a survival analysis technique.

*Fitting first-fixation duration with the ex-Gaussian distribution.* Figures 4 and 5 (see Panels a and b) display the distributions of first-fixation durations by text condition (normal, unsegmented). To create these figures, I separately computed the proportion of first-fixation durations that fell within each successive 25-ms bin over the range from 0 to 600 ms for each participant and each condition, and I then averaged these values across participants. As can be seen from Figures 4 and 5, the distributions of first-fixation durations tended to be approximately normal in shape with some degree of rightward skew. These distributions were modeled using the ex-Gaussian distribution, using the procedure described previously in Experiment 1. First-fixation duration data for each participant in each condition were fitted separately. The mean number of usable observations per cell ranged from 53 to 58 (see Table 7), and all fits
successfully converged. Table 7 displays the mean number of usable observations per cell, the parameter estimates, and the magnitude and significance of the word frequency effects, and Figures 4 and 5 (see Panels c and d) display the density functions generated from the best-fitting ex-Gaussian parameters averaged across participants.
Table 7
Number of observations per cell and ex-Gaussian parameters by text condition (normal vs. segmented), word frequency condition (high vs. low frequency), and Experiment (3A, 3B).
Standard errors are shown in parentheses.

<table>
<thead>
<tr>
<th></th>
<th>n</th>
<th>Mu (µ)</th>
<th>Sigma (σ)</th>
<th>Tau (τ)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Experiment 3A (within-subject manipulation)</strong></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Normal text</td>
<td></td>
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<td></td>
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<tr>
<td>Low Frequency</td>
<td>55 (0.4)</td>
<td>165 (2.6)</td>
<td>43 (1.7)</td>
<td>58 (2.3)</td>
</tr>
<tr>
<td>High Frequency</td>
<td>53 (0.5)</td>
<td>158 (1.8)</td>
<td>40 (1.3)</td>
<td>45 (2.3)</td>
</tr>
<tr>
<td>frequency effect</td>
<td>2***</td>
<td>7**</td>
<td>3</td>
<td>13***</td>
</tr>
<tr>
<td>Unsegmented text</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low Frequency</td>
<td>58 (0.9)</td>
<td>192 (3.1)</td>
<td>50 (2.1)</td>
<td>63 (2.9)</td>
</tr>
<tr>
<td>High Frequency</td>
<td>57 (1.0)</td>
<td>185 (2.9)</td>
<td>46 (1.7)</td>
<td>50 (2.5)</td>
</tr>
<tr>
<td>frequency effect</td>
<td>1***</td>
<td>7*</td>
<td>4*</td>
<td>13***</td>
</tr>
</tbody>
</table>

| **Experiment 3B (between-subjects manipulation)** |     |        |           |         |
| Normal text      |     |        |           |         |
| Low Frequency    | 56 (0.6) | 172 (3.5) | 41 (2.2)  | 59 (3.9) |
| High Frequency   | 53 (0.7) | 163 (2.8) | 37 (1.8)  | 50 (2.9) |
| frequency effect | 3*** | 9**    | 4         | 9**     |
| Unsegmented text |     |        |           |         |
| Low Frequency    | 58 (0.3) | 193 (3.8) | 51 (2.2)  | 65 (3.3) |
| High Frequency   | 57 (0.4) | 186 (3.1) | 45 (2.0)  | 53 (3.1) |
| frequency effect | 1*** | 7*     | 6**       | 12***   |

Note - For the t test results shown above, Experiment 3A df =103; Experiment 3B df =71; * p < .05, ** p < .01, *** p < .001
As shown in Table 7 and Figures 4 and 5, the overall pattern of ex-Gaussian results was the same for both Experiments 3A and 3B. Specifically, both the normal and the unsegmented text conditions produced a significant $\mu$ effect, such that the low frequency distribution was shifted to the right of the high frequency distribution, as well as a significant $\tau$ effect, such that the low frequency distribution also exhibited greater rightward skew as compared to the high frequency distribution. In addition, for the unsegmented condition (but not for the normal condition) there was a significant increase in $\sigma$ for the low frequency relative to the high frequency condition. This $\sigma$ effect might indicate that the amount of interference produced by unsegmented text is more variable for low frequency words than for high frequency words (for a related discussion, see White & Staub, 2012). Overall, the pattern of ex-Gaussian results replicates past findings that the word frequency manipulation produces both $\mu$ and $\tau$ effects under normal reading conditions (Reingold et al., 2012; Staub et al., 2010), and I extend this finding to the case of unsegmented text.

To further contrast the pattern of ex-Gaussian results across the unsegmented versus the normal conditions, I also performed 2 x 2 analyses of variance (ANOVA}s) for each experiment and each parameter, with text condition (normal, unsegmented), and word frequency (high, low) as independent variables. In both Experiments 3A and 3B, $\mu$ and $\sigma$ were significantly higher in the unsegmented condition relative to the normal condition in both experiments (all $F$s > 12, all $p$s < .01), and the $\tau$ parameter showed a similar effect that was significant in Experiment 3A ($F[1, 103] = 5.54, p < .05$), but not Experiment 3B ($F[1, 142] = 1.12, p = .293$). In addition, all three parameters ($\mu, \sigma, \tau$) were significantly higher for low frequency relative to high frequency words (all $F$s > 6, all $p$s < .05). There were no significant interactions (all $F$s < 1), which indicates that the word frequency effects on the ex-Gaussian parameters were similar in magnitude for the normal and the unsegmented text conditions.
Figure 4. Experiment 3A distributions of first-fixation duration on high-frequency and low-frequency targets in the normal text condition (Panel a) and unsegmented text condition (Panel b), and ex-Gaussian density functions (Panels c-d), and survival curves (Panels e-f) that were generated from these distributions (the row of asterisks at the top of Panels e-f indicate time bins with a significant differences between the low frequency and high frequency curves). See text for details.
Figure 5. Experiment 3B distributions of first-fixation duration on high-frequency and low-frequency targets in the normal text condition (Panel a) and unsegmented text condition (Panel b), and ex-Gaussian density functions (Panels c-d), and survival curves (Panels e-f) that were generated from these distributions (the row of asterisks at the top of Panels e-f indicate time bins with a significant differences between the low frequency and high frequency curves). See text for details.
Survival Analysis. I computed survival curves for first-fixation durations in the high and low frequency conditions, using the same procedure as Experiment 1. Specifically, for each 1-ms time bin $t$ ($t$ was varied from 0 to 600 ms), the percentage of first fixations with a duration greater than $t$ constituted the percent survival at time $t$. The survival curve was computed separately for each condition and for each participant, and then averaged across participants. As shown in Figures 4 and 5 (see panels e and f), the high and low frequency survival curves appear to diverge. Significant differences between the high and low frequency curves are shown in Figures 4 and 5 as a row of asterisks above the survival curves.

As seen from Figures 4 and 5, both of the experiments produced earlier divergence points in the normal condition relative to the unsegmented condition. Specifically, in Experiment 3A, the high and low frequency survival curves significantly diverged at a duration of 112 ms in the normal condition and 152 ms in the unsegmented condition, whereas in Experiment 3B the corresponding divergence points were 146 ms in the normal condition, and 169 ms in the unsegmented condition. Furthermore, the divergence point defines the percentage of first fixations with durations that were too short to exhibit an influence of word frequency. In

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6 I also used the survival analysis technique to examine the single-fixation and gaze duration measures, and my results were qualitatively similar to the first-fixation measure. Specifically, in Experiment 3A, the single-fixation divergence points were 100 ms in the normal condition and 166 ms in the unsegmented condition, and the gaze duration divergence points were 100 ms in the normal condition and 151 ms in the unsegmented condition. In Experiment 3B, the single-fixation divergence points were 142 ms in the normal condition and 178 ms in the unsegmented condition, and the gaze duration divergence points were 135 ms in the normal condition and 169 ms in the unsegmented condition. In the main text, I focus on the first-fixation measure that has been used in previous investigations (e.g., Reingold et al., 2012).
Experiment 3A, the percentage of first-fixation durations that were shorter than the divergence point was 5% in the normal condition and 9% in the unsegmented condition, whereas in Experiment 3B the corresponding percentages were 10% in the normal condition and 15% in the unsegmented condition. These percentages indicated that the vast majority of fixations were impacted by the word frequency manipulation, which is consistent with the ex-Gaussian findings that the word frequency manipulation produces a shift in the distribution (see Staub et al. 2010 for a related discussion). Finally, the survival analysis values for the normal condition in Experiment 3B closely replicate the results from a similar condition employed by Reingold et al. (2012).

To sum up, the above survival analyses indicate that the temporal onset of word frequency effects is delayed for the unsegmented relative to the normal condition, which strongly supports the hypothesis that the unsegmented condition delayed word identification (Rayner et al., 1998). In addition, there were later word frequency divergence points in Experiment 3B relative to Experiment 3A, for both the normal and unsegmented text conditions. Taken together with the global and target region analyses reported above, this difference across experiments suggests that lexical processing was more efficient for Experiment 3A, relative to Experiment 3B. This difference may have occurred because the within-subject manipulation in Experiment 3A exposed participants to a mixture of trial types, whereas the between-subjects manipulation in Experiment 3B employed only a single trial type (for related findings, see Lupker et al., 1997; Monsell et al., 1992; Rastle et al., 2003). However, I cannot rule out the alternative possibility that there were intergroup differences, such that the participants in Experiment 3A were more skilled readers than the participants in Experiment 3B. Most importantly, even though the overall level of reading performance differed across the experiments, the impact of the normal versus unsegmented text manipulation was still qualitatively similar for both of the experiments.
4.3 Discussion

Consistent with past work (e.g., Malt & Seamon, 1978; Morris et al., 1990; Perea & Acha, 2009; Pollatsek & Rayner, 1982; Rayner et al., 1998; Spragins et al., 1976; Yang & McConkie, 2001), removing interword spaces disrupted reading as indicated by longer fixation times, reduced reading rates, shorter saccades, and initial landing positions that were shifted towards the beginning of the word. Moreover, in replication of Rayner et al. (1998), the unsegmented text condition produced larger word frequency effects than normal text for the gaze duration and total time fixation time measures. As discussed by Rayner et al. (1998), such interactions suggest that unsegmented text interferes with word identification. Extending these findings, I employed a survival analysis technique (Reingold et al., 2012) to provide strong evidence that removing spaces delays the word identification stage of reading. Specifically, I derived estimates of the earliest influence of the word frequency variable, which is considered to be a good empirical marker of lexical processing (Reingold et al., 2012, Rayner, 1998, 2009a). Word frequency effects emerged as early as 112 ms from the start of fixation in the normal text condition, and as early as 152 ms in the unsegmented text condition. Thus, the unsegmented text condition produced a delay in the onset of word frequency effects, which indicates that removing spaces delays lexical processing. In addition, I used ex-Gaussian fitting to demonstrate that the word frequency variable produces both a shift and a skew effect under normal and unsegmented text conditions. Finally, both the survival analyses and the ex-Gaussian analyses revealed a qualitatively similar pattern of results regardless of whether the unsegmented versus normal text variable was manipulated within subject (Experiment 3A), or between subjects (Experiment 3B).
Most importantly, the survival analysis findings are consistent with the hypothesis that unsegmented text delays word identification (Epelboim et al., 1994, 1996; Morris et al., 1990; Pollatsek & Rayner, 1982; Rayner et al., 1998). As discussed by Rayner et al. (1998), there are several potential reasons for this delay, including the possibility that word segmentation is more difficult without spaces to demarcate which characters belong in a word (e.g., Li et al., 2009), as well as interference due to lateral masking (Bouma, 1973; Townsend et al., 1971). For the present study’s unsegmented text manipulation, word segmentation information was at least partially preserved because I replaced the spaces with non-letter fillers (i.e., random numbers between 2 and 9), and I avoided using numbers that might resemble letters (i.e., 1 and 0). However, these number fillers might have provided less predictable word segmentation cues than uniform fillers, such as the letter ‘x’ (see e.g., Rayner et al., 1998), and they might have produced additional processing difficulty if readers spent some of their time processing the numbers rather than the text. To further investigate the role of word segmentation processes, future research could test whether the delay in word frequency effects shown by the survival analysis would be more dramatic for unsegmented text manipulations that reduce word segmentation cues even further (e.g., by using random letters as fillers or by removing spaces entirely instead of using fillers).

Alternatively, the word identification delays might have been driven by lateral masking (Bouma, 1973; Townsend et al., 1971), such that the numbers interfered with the visibility of adjacent letters. Lateral masking has been previously discussed as a mechanism for explaining improvements in reading speed due to increases in interword spacing (e.g., Drieghe, Brysbaert, & Desmet, 2005; Rayner et al., 1998), increases in interletter spacing (Paterson & Jordan, 2010; Perea, Moret-Tatay, & Gómez, 2011), and increases in the amount of spacing between lines of text (Bentley, 1921; Chung, 2004). In the present study, the lateral masking explanation is
consistent with the fact that there were no qualitative differences as a function of strategic factors (i.e., the qualitatively similar pattern of results across Experiments 3A and 3B). In addition, it is possible that reduced parafoveal processing of target words in the unsegmented text condition partially contributed to the delays in word identification. In line with this explanation, the unsegmented text condition produced lower skipping rates than the normal condition, and prior work has shown that preventing parafoveal preview produces dramatic delays in the onset of word frequency effects during reading (Reingold et al., 2012).

Furthermore, the word identification delays could have occurred because unsegmented text constitutes an unfamiliar visual format for English readers. As discussed by Bai et al. (2008), a less familiar visual format would be expected to produce longer reading times relative to a familiar format. However, although familiarity may have played a role in the present study, prior results indicate that familiarity was not the sole cause of the delays produced by unsegmented text condition. Specifically, English readers were still impaired by unsegmented text even after they received extensive practice to familiarize them with the format (Malt & Seamon, 1978), and Thai (Winskel, Perea, & Ratitamkul, 2012; Winskel et al., 2009), Japanese (Sainio et al., 2007) and Chinese readers (Bai et al., 2008; Shen et al., 2012) have occasionally shown improvements after spaces were added to the text, even though unsegmented text is the more familiar format for these languages. Clearly, further work is required to ascertain the exact mechanisms that led to a delay in the onset of word frequency effects in the unsegmented text condition.

In addition to the survival analyses, ex-Gaussian fitting was used to compare the time course of word frequency effects in the normal and unsegmented text conditions. As mentioned previously, the word frequency variable produced both a shift and a skew effect under both
normal and unsegmented text conditions, which replicates the pattern of results that was shown previously for normal text (Reingold et al., 2012; Staub et al., 2010). The presence of a shift effect indicates that the word frequency variable was fast-acting enough to influence the vast majority of fixations, in both the normal and unsegmented text conditions (Staub et al., 2010). More generally, there is now ample evidence that reading performance is impacted by a variety of manipulations of the visual appearance of the text, including typography (e.g., Barnhart & Goldinger, 2010; Kolers, 1968; Paterson & Tinker, 1947; Rayner, Reichle, Stroud, Williams, & Pollatsek, 2006; Sheridan & Reingold, 2012; Slattery & Rayner, 2010; Tinker & Paterson, 1955), stimulus quality (e.g., Reingold & Rayner, 2006; White & Staub, 2012), and interword spacing (e.g., Rayner et al., 1998). Empirical findings concerning the visual characteristics of the text can provide insights into the complex processes that support skilled reading, and can inform models of eye movements control during reading (for reviews, see Rayner, 1998, 2009a). For example, the E-Z Reader model (Reichle et al., 1998) was extended to Chinese text, which does not contain spaces (Rayner, Li, & Pollatsek, 2007), and was used to generate novel predictions concerning the impact of typography and stimulus quality manipulations (Reingold & Rayner, 2006). In the present study, I provide convergent evidence for the hypothesis that removing spaces during reading interferes with both word identification and saccadic programming (Rayner et al., 1998), and my findings highlight the usefulness of distributional analyses in providing fine-grained time course information that is not available from mean analyses alone.
5 Conclusions

The present thesis employed distributional analyses of fixation times to provide fine-grained information concerning the time course of lexical influences during skilled reading. In four experiments, I used ex-Gaussian fitting (Staub et al., 2010) and a survival analysis (Reingold et al., 2012) to demonstrate that a wide range of lexical variables can have a fast-acting influence on the vast majority of fixation times during reading. These findings help to clarify the nature of the eye-mind link during reading, by showing that ongoing lexical and linguistic processing can have an immediate impact on eye movement control. In the following section, I will summarize my main findings and I will then discuss the implications of these findings for models of eye movement control during reading (for reviews, see Rayner, 1998, 2009a) and for future research directions.

In Experiment 1, I investigated the time-course of predictability effects during reading, by contrasting distributions of first-fixation durations on target words (e.g., teeth) in a high-predictability prior context (e.g. “The dentist told me to brush my teeth to prevent cavities.”) versus a low-predictability prior context (e.g., “I'm planning to take better care of my teeth to prevent cavities.”). In replications of Staub (2011), ex-Gaussian fitting revealed a shift effect, such that the low predictability distribution was significantly shifted to the right of the high predictability distribution. This finding supports an early time-course of predictability effects, because a shift effect indicates that a variable was fast-acting enough to influence both long and short fixation times (for further discussion, see Staub et al., 2010). To extend this finding, I used a survival analysis technique (Reingold et al., 2012) to derive a quantitative estimate of the earliest significant influence of predictability on fixation times. This survival analysis revealed
that predictability effects emerged as early as 140 ms from the onset of fixation, which is similar to Reingold et al. (2012)’s finding that word frequency effects emerged as early as 145 ms during normal reading. Taken together, these findings provide strong evidence that predictability has a fast acting influence on fixation times during reading.

In Experiment 2, I used the distributional analysis techniques from Experiment 1 to investigate the nature of lexical ambiguity effects during reading. Specifically, I examined the well-established finding that readers experience processing difficulties when they encounter biased homographs in a subordinate-instantiating prior context (i.e., the subordinate bias effect; for a review see Duffy et al., 2001). To investigate the time course of this effect, I contrasted distributions of first-fixation durations on biased homographs (e.g., suit) in a subordinate-instantiating context (e.g., “The law firm agreed to represent me in the suit that was filed last week.”) versus in a dominant-instantiating context (e.g., “I went to the dry cleaners to pick up the suit that I'm wearing to the wedding.”). Ex-Gaussian fitting revealed that the subordinate context distribution was shifted to the right of the dominant context distribution, and the survival analysis technique showed a significant influence of the subordinate vs. dominant contextual manipulation as early as 139 ms from the start of fixation. This early effect lends support to models of lexical ambiguity resolution that assume that prior context can impact the early lexical access stage of reading (for a review, see Duffy et al., 2001). Moreover, Experiment 2 replicates Experiment 1 by showing that lexical ambiguity effects can be equally rapid as other lexical variables, such as predictability and word frequency.

In Experiments 3A and 3B, I employed distributional analyses to examine the role of interword spaces during reading. The main goal of these experiments was to investigate Rayner et al. (1998)’s hypothesis that removing spaces during reading can interfere with lexical
processing. To test this hypothesis, I contrasted the time-course of word frequency effects during normal reading relative to an unsegmented text condition that did not contain interword spaces. Most importantly, the survival analysis technique revealed a later time course of word frequency effects in the unsegmented relative to the normal condition, such that the earliest discernible influence of word frequency was 112 ms from the start of fixation in the normal text condition, and 152 ms in the unsegmented text condition. This delay in the onset of word frequency effects occurred regardless of whether the unsegmented versus normal text variable was manipulated within subject (Experiment 3A), or between subjects (Experiment 3B). Given that word frequency effects are a marker of lexical processing, this finding indicates that lexical processing was delayed in the unsegmented relative to the normal text condition. In addition, Experiments 3A and 3B replicated prior ex-Gaussian findings (Reingold et al., 2012; Staub et al., 2010) by showing that the word frequency variable is fast-acting enough to produce a shift effect for both the unsegmented and normal text conditions, such that distribution of first-fixation times was shifted to the right for the low frequency relative to the high frequency condition. Thus, Experiments 3A and 3B build on Experiments 1 and 2 by demonstrating fast-acting word frequency effects, and by showing that interword spacing can facilitate lexical processing.

Taken together, the findings from the present thesis contribute to the long-standing debates over the nature of the eye-mind link during reading (for review, see Rayner, 1998, 2009a). In these debates, a great deal of controversy has surrounded the extent to which higher level lexical and linguistic processing can have an immediate impact on fixation times (i.e., direct cognitive control). In support of direct cognitive control, the present thesis used ex-Gaussian fitting to demonstrate that three lexical variables (i.e., word frequency, predictability, and lexical ambiguity) can be fast acting enough to produce a shift in the entire distributions of fixation times. Building on this finding, the survival analysis revealed that the earliest onset of
lexical influences on fixation times was 112 ms for word frequency, 140 ms for predictability, and 139 for predictability, and only a small proportion of fixation durations (i.e., 15% or less) were shorter than these temporal estimates. Taken together with prior findings (Reingold et al., 2012; Staub et al., 2010; Staub, 2011), these distributional analysis results provide strong evidence that lexical variables can produce a rapid effect on the vast majority of fixation times during reading.

The temporal estimates from the present thesis are also consistent with prior work that used electrophysiological methods to establish the minimal latencies at which lexical variables first begin to produce differential brain responses. Specifically, as reported by Sereno and colleagues, ERP research has demonstrated word frequency effects (Sereno et al., 1998) and predictability effects (Sereno et al., 2003) as early as 132 ms post-stimulus onset. More recently, ERP studies have shown word frequency effects as early as 102 ms post-stimulus onset (Reichle et al., 2011), as well as interactions between word length and frequency as early as 110 ms post-stimulus onset (Penolazzi, Hauk, & Pulvermüller, 2007). Furthermore, experiments using magnetoencephalography (MEG) have shown very early (i.e., 60-90 ms post-stimulus onset) effects of word length in conjunction with rapid (i.e., 120 ms post-stimulus onset) effects of word frequency (Assadollahi & Pulvermüller, 2001, 2003). These early lexical effects are particularly remarkable given that it takes approximately 50 ms for visual information to travel from the retina to the brain (i.e., the “eye-to-brain” lag; Clark et al., 1995; Foxe & Simpson, 2002; Mouchetant-Rostaing et al., 2000; Van Rullen & Thorpe, 2001), and given that these electrophysiological studies involved the presentation of single letter strings, such that no parafoveal preview was available. As discussed by Reingold et al. (2012), normal reading conditions are even more conducive to fast-acting lexical influences because readers can use
prafoveal processing to begin to process upcoming target words during fixations on the pre-target word.

In addition, the early lexical effects shown by electrophysiological and eye tracking studies are consistent with another line of research that employed the “disappearing text” paradigm (Blythe et al., 2009; Ishida & Ikeda, 1989; Liversedge et al., 2004; Rayner et al., 1981, 2003). In these studies, word frequency effects were preserved even when the text disappeared 60 ms after the start of the first fixation on high and low frequency target words. This finding demonstrates that word frequency effects can be solely driven by visual information obtained from parafoveal preview and/or from visual input obtained during the first 50 ms of the first fixation on the target words.

Thus, there is growing evidence that ongoing lexical and linguistic processing during reading is fast-acting enough to influence the vast majority of fixation durations. Collectively, this evidence supports the viewpoint that there is a strong eye-mind link, such that eye movements during reading are tightly linked to ongoing higher-level cognitive processes. This viewpoint is consistent with models of eye movement control that assume that lexical and linguistic influences play a non-trivial role in driving fixation times during reading (e.g., Engbert et al., 2002, 2005; Just & Carpenter, 1980, 1987; Kliegl & Engbert, 2003; McDonald et al., 2005; Morrison, 1984; Pollatsek, Reichle, & Rayner, 2006; Reichle et al., 1999; 2003, 2006; Reilly & Radach, 2003, 2006; Reingold et al., 2010; Richter et al., 2006; Thibadeau et al., 1982), and is difficult to reconcile with models that assume that lexical effects are limited to a small subset of long fixations and that the vast majority of reading fixations are unaffected by these variables (e.g., Deubel et al., 2000; Feng, 2006; 2012; McConkie & Yang, 2003; Yang & McConkie, 2001; Yang, 2006).
However, the extensive evidence for fast-acting lexical influences does not diminish the fact that a wide range of visual and oculomotor variables can also have a strong influence on fixation durations (for further discussion, see e.g., McConkie et al., 1988; Vitu, 2001). Indeed, distributional analyses of fixation times have recently demonstrated rapid effects for several non-lexical variables, including fixation location (Reingold et al., 2012), and stimulus quality (White & Staub, 2012). Thus, to account for the complete pattern of eye movements during reading, models of eye movement control must make allowances for both lexical and non-lexical influences on fixation durations. In summing up this viewpoint, Reichle et al. (2003) notes that the historical dichotomy between oculomotor and processing models is now better thought of as a continuum, in light of that fact that more recent models now place varying degrees of emphasis on both lexical and non-lexical influences.

In addition to incorporating both lexical and non-lexical influences, models of eye movement control must also accommodate the time-course of these effects. In particular, models must incorporate some type of direct control mechanism in order to account for why lexical influences exert a rapid influence the vast majority of fixation times during normal reading. One possible direct control mechanism was proposed by E-Z Reader. Specifically, according to the E-Z Reader model, the initiation of the programming of a saccade to the next word (word_{n+1}) is triggered by the completion of an early stage of lexical processing (L_1), which indicates that lexical access is imminent. Importantly, by assuming that fixation durations on word_n are determined by an early stage of lexical processing, rather than the completion of lexical access (see Just & Carpenter, 1980), the E-Z Reader model is better able to accommodate rapid lexical effects. Consequently, the E-Z Reader model has successfully modeled word frequency and predictability effects (Reichle et al., 1998), as well as lexical ambiguity effects (Reichle et al., 2006), by assuming that these variables impact the duration of the L_1 stage.
In addition to the E-Z Reader model, other instantiations of direct cognitive control might also be compatible with rapid lexical effects on fixation times. For example, the SWIFT model (Engbert et al., 2002, 2005) incorporates the assumption that lexical processing difficulty associated with the currently fixated word (word_n) can lengthen fixation times by actively inhibiting the initiation of new saccadic programs through a process known as foveal inhibition. Although time delays in the foveal inhibition process may result in longer fixation on word_{n+1} rather than on word_n (Engbert et al., 2005), the foveal inhibition mechanism constitutes an example of direct cognitive control because it is based on local processing and it can (at least occasionally) impact fixation durations on word_n. Thus, the eye movement control literature currently contains multiple possible direct control mechanisms, and further work is needed to distinguish between them.

Moreover, further work is needed to clarify the boundary conditions that are necessary for producing fast-acting cognitive influences on fixation times. Towards this end, Reingold et al. (2012) have already demonstrated that parafoveal processing plays a key role in enabling fast-acting lexical influences on fixation times, by showing that word frequency effects were dramatically delayed under no preview conditions relative to preview (i.e., normal reading) conditions. However, parafoveal processing did not appear to impact non-lexical effects on fixation times because Reingold et al. (2012) demonstrated that the impact of fixation location on fixation durations was equally rapid with and without preview. In the present dissertation, I further clarified the conditions that facilitate lexical processing by showing that word frequency effects are delayed in the unsegmented text condition relative to normal reading conditions. Future work could continue to explore the conditions that facilitate fast-acting lexical influences.
Finally, future research could continue to use the distributional analysis techniques from the present thesis to provide fine-grained time-course information that cannot be obtained from mean analyses alone. The present thesis demonstrates that distributional analyses can be used to investigate a wide range of topics, including models of eye movement, theories lexical ambiguity resolution and the role of interword spaces in reading. Building on the present thesis, future work can continue to apply these techniques to reading as well as to other domains of visual expertise, such as chess and medical expertise (Reingold & Sheridan, 2011), in order to explore both reading-specific and domain-general characteristics of the eye-mind link.
References


Appendix A: Low predictability and high predictability sentences used in Experiment 1

For each pair of sentences, sentence “L” refers to the low-predictability sentence, and sentence “H” refers to the high-predictability sentence. The target words are shown in italics.

1L) Howard found a nest in the big oak tree.
1H) The bird was building a nest in the big oak tree.

2L) He asked for something sweet to eat after dinner.
2H) I ordered the cake, because I felt like something sweet to eat after dinner.

3L) I ran after the sheep that jumped over the gate.
3H) The shepherd ran after the sheep that jumped over the gate.

4L) Dan pointed at the clock on the wall.
4H) To check the time, he looked at the clock on the wall.

5L) I complained because the young couple went in front of me in the line.
5H) On their wedding anniversary, the young couple went downtown to see a show.

6L) Monica told the driver to take her to the airport.
6H) She entered the taxi and told the driver to take her to the airport.

7L) I noticed a signal from the lighthouse on top of the hill.
7H) The sailors waited for the lighthouse to send a signal from the coast.

8L) Henry complained that it was so bright that it was nearly blinding.
8H) She squinted because the sunlight was so bright that it was nearly blinding.

9L) Peter says that a muscle in his leg was bothering him during soccer practice.
9H) The athlete pulled a *muscle* in his leg during the competition.

10L) My rich uncle just purchased an *island* in the Caribbean.

10H) The sailors were stranded on an *island* in the Caribbean.

11L) There was a leather *saddle* on top of the shelf in the barn.

11H) My horse has a leather *saddle* and a black harness.

12L) The girl found the *mirror* on the dresser.

12H) The girl looked at her reflection in the *mirror* on the dresser.

13L) The students met downtown for *dessert* and snacks every Friday.

13H) Following dinner, she ordered ice cream for *dessert* and asked for the bill.

14L) Jennifer frowned at the dirty *clothes* and boots.

14H) On laundry day, she picked up the dirty *clothes* and put them into the washer.

15L) Sam decided that the one *million* dollars should be donated to charity.

15H) The jackpot for the lottery is at over one *million* dollars this week.

16L) Paul was asked to complete a *mission* of great importance.

16H) The secret agent was sent on a *mission* of great importance.

17L) Mathew enjoys European *history* because of the many interesting royal families.

17H) The Middle Ages were a dark time in European *history* because of the many wars.

18L) I heard that Hank has one *brother* from his Dad's first marriage.

18H) Bob has two sisters and one *brother* from his Dad's first marriage.

19L) He hoped to see some changes in the *economy* before long.

19H) The recession is over, so there will be improvements in the *economy* before long.

20L) Ruth asked me to bring her the *newspaper* this morning.

20H) Gail read an interesting article in the *newspaper* this morning.
21L) Wendy was standing in the snow next to the house.

21H) In the winter, the kids love to play in the snow next to the house.

22L) Karen needed a small amount of flour and three eggs for the recipe.

22H) The cake recipe required two cups of flour and three eggs.

23L) I'm planning to take better care of my teeth to prevent cavities.

23H) The dentist told me to brush my teeth to prevent cavities.

24L) Mary looked at the floor in her kitchen to check if it needed cleaning.

24H) Lisa used a broom to sweep the floor in her kitchen.

25L) There is a wooden shelf beside the window in my room.

25H) There is a nice view outside of the window in my room.

26L) It was very difficult to escape from the dungeon.

26H) The prisoner was planning to escape from the dungeon.

27L) Today the class learned about a large planet that has over ten moons.

27H) Jupiter is a large planet that has a red spot and many moons.

28L) Marlene decided that the extra weight from her pregnancy did not bother her.

28H) Rachel went to the gym to lose some extra weight from her pregnancy.

29L) Tom first heard about the slim chance of a strike while talking to his boss at lunch.

29H) I don't buy lottery tickets because there is such a slim chance of winning.

30L) There are lots of rocks on the bottom of the ocean.

30H) The ship had sunk to the bottom of the ocean.

31L) The man was carrying a weapon during the attack last night.

31H) The knife was used as a weapon during the attack last night.

32L) The funds were used to replace the bridge after the earthquake.
32H) We crossed over the bridge after entering the town.

33L) I went to visit the community college near my home.

33H) Instead of going to university, I studied at a community college near my home.

34L) We decided to visit the shelter near the hospital.

34H) We served soup to the homeless at the shelter near the hospital.

35L) Sarah frowned when she saw the mistake on her test.

35H) Myra used an eraser to fix the mistake on her test.

36L) The empty lot was covered with the garbage from the neighbourhood kids.

36H) She walked to the dumpster to throw away the garbage from the basement.

37L) I will be leaving from the station at noon today.

37H) The train is leaving from the station at noon today.

38L) I was amazed that there was so much traffic on the highway.

38H) The driving was slow because there was so much traffic on the highway.

39L) A legal contract is a promise or an agreement between two groups of people.

39H) A trustworthy person will never break a promise or tell a lie.

40L) Joe didn't know what to make for breakfast this morning.

40H) Ron ate cereal for breakfast this morning.
Appendix B: Subordinate-instantiating and dominant-instantiating sentences used in Experiment 2

For each pair of sentences, sentence “S” refers to the subordinate-instantiating sentence, and sentence “D” refers to the dominant-instantiating sentence. The target words are shown in italics.

1S) At the comedy show, I laughed at the funny behaviour of the ham on the stage.
1D) During dinner last night, Joey ate all of the ham on his tray.

2S) The cops arrested Mike for drug dealing, because they found the pot in his bag.
2D) To boil the water, Luke used the pot in his kitchen drawer.

3S) The weightlifter picked up the bar with the fifty pound weights.
3D) My friend is a waitress at the bar with the red sign on the door.

4S) In Florida, the most common tree is the palm because it thrives in a warm climate.
4D) The most sensitive part of the hand is the palm because it has lots of nerve cells.

5S) The room was warm, but there was a breeze coming from the fans in the ceiling.
5D) The famous actor received lots of compliments from the fans in the audience.

6S) An abstract summarizes the ideas that are discussed in the body of the paper.
6D) The police found two gunshot wounds in the body of the victim.

7S) After shuffling the cards, I put them back on the deck in front of the dealer.
7D) During the summer, I love sitting on the deck in front of my house.

8S) While fishing in the river, I often sit on the bank near the rocks.
8D) After graduation, my friend got a job at the bank near the mall.
9S) The royal family admired the singing of the page in the choir.

9D) I wrote some comments in the margin of the page in the textbook.

10S) Polly listened to the first song of the tape with great enthusiasm.

10D) Hanah tried to tear off a piece of the tape with her fingers.

11S) Amy had to replace her watch, because the buckle on the band was broken.

11D) At the concert, I enjoyed listening to the songs that the band was performing.

12S) The duck had brown feathers and a bill that was wide and flat.

12D) At the store, the cashier gave me a bill that was worth one dollar.

13S) A flat surface is called a plane and a round object is a sphere.

13D) While gazing at the sky, I saw a plane and a small helicopter.

14S) The hunting laws protect the deer, so that the bucks are not killed for their antlers.

14D) I give money to charity, because I know that the bucks are going to a good cause.

15S) My dentist says my tooth will need a new crown at my next appointment.

15D) The young queen was wearing a new crown at her coronation.

16S) To cast the spell, the wizard recited the symbols on the staff in his hand.

16D) The office is closed on Fridays because the staff in the building is on holidays.

17S) Lightning struck the tree during the storm, and its trunk was badly damaged.

17D) My car needs repairs, because its trunk was badly damaged in the accident.

18S) At the basketball tournament, I sat close enough to the court to see everything.

18D) During the legal trial, the judge spoke to the court to explain the rules.

19S) Kyle is scared of dogs because he was attacked by the boxer with the brown fur.

19D) Fred was punched in the face by the boxer with the brown gloves.

20S) The pregnant woman was looking forward to becoming a new mummy in a month.
20D) In Egypt, the brave explorer discovered a new mummy in the ancient tomb.

21S) John was appointed to be a member on the board in his father's company.

21D) The chess player examined the pieces on the board in front of him.

22S) The stable boy tied the horses to the coach at the side of the barn.

22D) The captain of the football team spoke to the coach at the side of the room.

23S) You have to pay to enter the club on Saturdays, but the cover is free on weekdays.

23D) I bought the book because the picture on the cover is interesting.

24S) My diet includes a variety of foods, but rice is a staple in the winter.

24D) I attached the documents with a staple in the corner.

25S) To keep the flies out, I closed the screen on the door.

25D) To upgrade my computer, I replaced the screen on the monitor.

26S) The waitress removed my glasses and my empty bowl.

26D) On the first day of school, I wore my glasses and my favourite hat.

27S) The researcher's birth rate statistics are from the records at the town hall.

27D) Ben's favourite songs are from the records at the music store.

28S) To monitor the number of online users, the website has a counter at the top.

28D) To provide extra surface space, the kitchen has a counter at the side of the room.

29S) Be careful while climbing the stairs, because some of the flights don't have railings.

29D) You should buy lunch at the airport, because some of the flights don't serve meals.

30S) The criminal spent a long time in jail, because the sentence was very severe.

30D) I had trouble reading the paragraph, because the sentence was very confusing.

31S) The card players decided to play a round of gin before dinner.

31D) I asked the waitress to bring us a bottle of gin before dinner.
At the petting zoo, the cutest goat was the kid with the floppy ears.

On the playground, the teacher scolded the kid with the blue sneakers.

The pigs are inside the pen on the south side of the barn.

I wrote my name with the pen on the desk.

The hiker rolled up his jeans to put ice on the calf that was injured.

After milking the cows, the farmer fed the calf that was born last night.

At the movie premier, we spoke to the biggest star in the new movie.

The telescope was pointed to the biggest star in the northern hemisphere.

Before the secret meeting, the spy dismantled all of the bugs in the room.

The pest exterminator used poison to get rid of all of the bugs in the room.

The jar was leaking, because the seal in the lid was broken.

While visiting the zoo, I enjoyed watching the seal in the tank.

The odds of winning were lousy, so I didn't place a bet in the pool at my office.

During the summer, the children loved going to the pool at the community centre.

The law firm agreed to represent me in the suit that was filed last week.

I went to the dry cleaners to pick up the suit that I'm wearing to the wedding.

During the war, the smugglers raised the price of their arms and their guns.

Many people have tattoos on their arms and their back.

The circus performers stood inside the ring at the end of the show.

I couldn't afford to buy the ring at the expensive jewelry store.

George was informed of the news by the wire that was sent on Monday.

The electrician was standing by the wire that was connected to the power outlet.

The best man at the wedding prepared some jokes for the toast and the speeches.
43D) There was no butter for the toast and the eggs were overcooked.

44S) I had to turn the car quickly to adjust to the crook in the road.

44D) The police officer spoke to the crook in the back of the police car.

45S) The factory workers lost their jobs after the closing of the plant this week.

45D) The gardener trimmed the leaves on the plant this morning.

46S) The gardener planted the bulbs in the dirt beside the house.

46D) The janitor replaced the bulbs in the lamps.

47S) Below the earth's surface, there is a thick crust that is made of rocks and sand.

47D) On the pizza, there is a thick crust that is made of all-natural ingredients.

48S) The used car salesman asked me to pay him the dough for the car.

48D) The baker used a large bowl to mix together the dough for the bread.

49S) Before going to church, the nun put on the habit and her white gloves.

49D) Kim still smokes, but she is trying to stop the habit and her health is a priority.

50S) After arriving at the castle, the knight met with his ruler to discuss the war plans.

50D) Josh measured the box with his ruler to check if it was large enough.

51S) The musician enjoys composing music for the organ that belongs to the church.

51D) The doctor found a recipient for the organ that was donated this morning.

52S) During the Ice Age, most of the land was covered by a large sheet of ice.

52D) The notice was written on a large sheet of white paper.

53S) To dig the hole, the gardener needed a spade and a bucket.

53D) The card dealer gave the poker player a spade and an ace.

54S) Alan played golf on the new course at the resort.

54D) The student asked for more information about the new course at the university.
55S) The scientist measured the beaker to determine the volume of the liquid.

55D) Sally adjusted the volume of the television.

56S) Bob's stroke led to some memory loss, but he retained the faculty of speech.

56D) Next semester, I'm taking a math class in the faculty of engineering.

57S) The baseball player didn't like the throwing style of the pitcher with the blue hat.

57D) Jane served the lemonade in the pitcher with the blue handle.

58S) Before the experiment, the researcher spoke to the subject in the hallway.

58D) The students enjoyed learning about the subject in class today.

59S) The company is a good investment because its capital is very secure.

59D) Spain is a good country to visit because its capital is very beautiful.

60S) At age ten, Mozart composed the first movement in his famous symphony.

60D) The dance instructor demonstrated the first movement in the sequence.
Appendix C: High frequency and low frequency target words and sentences used in Experiments 3A and 3B

For each pair of sentences, the two possible target words are shown in italics, separated by a dash (high frequency/low frequency).

1A) Jim wanted to buy the *chair/cloak* that was on display in the window.
1B) Rose found a new *chair/cloak* at the bazaar.

2A) To make his mom happy, Tim took another *piece/patty* and ate it.
2B) He dropped a *piece/patty* while carrying the tray across the room.

3A) John decided to sell the *table/banjo* in the garage sale.
3B) I was told that the *table/banjo* was made out of expensive wood.

4A) He ran away from the *crowd/troll* and hid behind a wall.
4B) To escape from the pouring rain, the *crowd/troll* hid under a large tree.

5A) I felt the wind on my face when the *train/racer* flew by me.
5B) Jeanette was amazed that the *train/racer* was so fast.

6A) Amy sat down on the *stage/quilt* and crossed her legs.
6B) Alice began to decorate the *stage/quilt* in preparation for the fair.

7A) The noise coming from the *motor/flute* was too loud for their ears.
7B) Carmen looked at the shiny *motor/flute* with admiration.

8A) I found the *story/icing* to be kind of bland.
8B) Nora enjoyed the *story/icing* even though no one else did.

9A) Mary removed the *cover/gauze* using her thumb and index finger.
9B) The laser burned through the cover/gauze and left it in shreds.

10A) Everyone stayed away from the block/plaza where the fight had happened.

10B) Vendors took over the block/plaza without any permission from the city.

11A) We stepped into the small space/hovel and looked around cautiously.

11B) I saw that the space/hovel was full of dirt and grime.

12A) In the darkened room, the voice/audio seemed to come out of nowhere.

12B) I complained because the voice/audio was too difficult to hear.

13A) I heard that the judge/valet was very well paid.

13B) It was necessary for the judge/valet to give them some instructions.

14A) The curious little boy saw the horse/roach and ran towards it.

14B) There was a large horse/roach inside the shed.

15A) It was an unfortunate issue/fluke that I would like to forget.

15B) Jennifer admitted that the issue/fluke had caught her by surprise.

16A) The farmer picked up the plant/melon and carried it to the truck.

16B) Sally bought a plant/melon from the stall at the side of the road.

17A) It was upsetting to hear about death/polio on the evening news.

17B) The class discussion about death/polio caused a great deal of fear.

18A) Yesterday, I found a woman/medic standing near the store front.

18B) The tourists were mesmerized by the woman/medic with the flashy uniform.

19A) We were concerned that her heart/colon would not recover from the surgery.

19B) Clair was studying the heart/colon in preparation for the anatomy exam.

20A) Ben and John had been planning the party/heist for months.

20B) We were relieved that the party/heist went smoothly.
21A) We tricked the kids into cleaning the water/slime out of the old barrel.
21B) Samantha had to remove the water/slime from the basement.
22A) He examined the radio/rhino with interest.
22B) The boy admired the radio/rhino even though it bored his little sister.
23A) The mayor went to the event/vigil even though his schedule was busy.
23B) The road was closed because of the event/vigil that was happening later that evening.
24A) Beth ran her fingers along the board/tunic and was shocked at its roughness.
24B) I picked up the board/tunic that had been left haphazardly on the ground.
25A) She found a dress/skunk inside the box in the garage.
25B) Jessica told us about the dress/skunk that she had seen.
26A) She was very proud of her smile/girth and her sense of fashion.
26B) The man was distinctive because of his smile/girth and his loud laugh.
27A) Jenn swallowed in fear when a light/robin came out of the cave.
27B) Henry noticed a light/robin near the top of the roof.
28A) In my dream, the scene/oasis was filled with lush greenery.
28B) She stared at the scene/oasis on the other side of the river.
29A) Tom first heard about the trial/toxin from his tutor.
29B) She decided to ask about the trial/toxin to learn more about it.
30A) Everyone agreed that the night/broth had been better than usual.
30B) Samuel was surprised that the night/broth was still so blistering hot.
31A) None of the kids wanted to play the part of the enemy/gnome in the play.
31B) He saw the enemy/gnome on the other side of the trees.
32A) I pointed at the hotel/pooch on the other side of the road.
32B) Angela loved to talk about the hotel/pooch that her uncle owned.

33A) It was difficult to make the drink/curry because of all the ingredients.

33B) She decided to try the drink/curry because her buddy had recommended it.

34A) Janice picked up the tooth/acorn and put it in her pocket.

34B) Timmy found the tooth/acorn on a bench in the park.

35A) The young girls laughed at the silly dance/spoof the jester was performing.

35B) Mike told us about the dance/spoof from the day before.

36A) She began to mold the earth/crust with her fingers.

36B) It appeared that the earth/crust had dried out and hardened.

37A) We were afraid of the chief/crone because of the rumours.

37B) He listened carefully when the chief/crone began to speak.

38A) Jim entered the abandoned house/crypt and looked around nervously.

38B) She walked by the house/crypt every day on her way to work.

39A) The sudden knock/chirp from outside startled Tina.

39B) I tried to figure out where the knock/chirp had come from.

40A) Jamie complained that the place/kiosk was a bit too small.

40B) Absolutely everyone was in awe of the place/kiosk after the renovations.

41A) Aisha complimented her cousin's garden/bonnet even though she was secretly jealous.

41B) I was distracted by the garden/bonnet because of its bright colours.

42A) She was annoyed because the system/zipper could not be replaced.

42B) Lena told me that the system/zipper was broken again.

43A) Kelly and George were looking forward to their dinner/brunch at the new restaurant.

43B) Tony was nervous about the dinner/brunch because his boss was going to be there.
44A) They were proud of the church/cohort for raising so much money for charity.
44B) Most members of the church/cohort were in favour of the new policies.
45A) The messenger told Olivia to hide the weapon/amulet from the sorcerer.
45B) The museum contained an old weapon/amulet that had once belonged to royalty.
46A) After the little cabin burned down, the family/damsel had nowhere left to go.
46B) As soon as the war erupted, the family/damsel fled from the kingdom.
47A) Almost nobody knew about the bridge/ravine on the east side of town.
47B) Be careful near the bridge/ravine because the ground is slippery.
48A) Karen went to the doctor/matron and asked for advice.
48B) In the small town, the doctor/matron was very well-respected.
49A) Anne told them to avoid the forest/cavern because many dangers lurked there.
49B) There was a large forest/cavern near my grandfather's home.
50A) It was obvious that the rundown street/duplex would need major repairs.
50B) The elderly lady was surprised that the old street/duplex had not changed at all.
51A) The city had been home to the artist/beggar for most of his life.
51B) The kids stared at the artist/beggar with the green hat.
52A) Joan went to her friend/mentor for advice about her finances.
52B) The young executive felt certain that his new friend/mentor was trustworthy.
53A) Everyone knew that the animal/badger was dangerous.
53B) The little girl wanted to touch the animal/badger but she ran away when it snarled.
54A) The girl hoped that her mother/healer would be able to help her.
54B) Larry stayed home because his mother/healer had told him to rest.
55A) Rachel noticed the object/spider just before she stepped on it.
55B) She knew that the *object/spider* was probably harmless.

56A) Allen was confused by the *answer/module* in the textbook.

56B) He was relieved that the *answer/module* had been finalized before the deadline.

57A) When his truck broke down, Toby asked the *police/ranger* for help.

57B) When the little girl went missing, the *police/ranger* searched everywhere.

58A) It was important to find the *letter/carton* before anyone noticed it was missing.

58B) Suzie carried the *letter/carton* into her room.

59A) The pirate king needed to discuss the *attack/bounty* with his crew.

59B) Larry was convinced that the *attack/bounty* was not worth the effort.

60A) The confusing and complicated *design/rubric* was going to be very unpopular.

60B) Boris could not understand the *design/rubric* that Mike had given him.

61A) It was time for the *leader/sniper* to make a decision.

61B) It was difficult for the *leader/sniper* to predict what was about to happen.

62A) She went to the *market/pantry* to get some vegetables for the stew.

62B) Billy was sent to the *market/pantry* to find some spices.

63A) The shop owner waited impatiently for the *supply/toffee* to be delivered.

63B) Rodney was excited about the *supply/toffee* that his cousin gave him.

64A) Alex was upset when the *demand/felony* was made public.

64B) According to the reporter, the *demand/felony* was very unusual.

65A) He enjoyed sitting next to the *editor/tycoon* at the banquet.

65B) Although the news was unfortunate, the *editor/tycoon* remained optimistic.

66A) Kim wanted to meet at the *office/bakery* but Jess thought this was a bad idea.

66B) He couldn't find the *office/bakery* because it had moved to a new location.
67A) The package was delivered to the school/scribe first thing in the morning.

67B) Tom knew that the school/scribe had a good reputation.

68A) The nurse knew that stress/scurvy was a concern.

68B) The captain was concerned that stress/scurvy was affecting his men.

69A) William majored in science/algebra because he loved the subject.

69B) Clive hates studying science/algebra because he finds it very hard to understand.

70A) Christine put the remaining money into her account/satchel for safekeeping.

70B) Please take sixty dollars out of the account/satchel and use it to pay the plumber.

71A) Liz showed us a photo of her husband/toddler during lunch the other day.

71B) Diana rushed her husband/toddler to the hospital after he fell and hurt himself.

72A) The nurse said that Dad's trouble/amnesia was only temporary.

72B) Unfortunately, my neighbour's trouble/amnesia started when she turned seventy.

73A) We could tell from the quality/emerald that the necklace was very expensive.

73B) Ruth admired the ring's quality/emerald and asked Becky where it was purchased.

74A) At the meeting, the officer/admiral gave a short presentation.

74B) They asked the officer/admiral at the embassy for help.

75A) I was amazed that Sean was able to repair the broken machine/trellis so quickly.

75B) Peter climbed to the top of the large machine/trellis in order to clean it thoroughly.

76A) Please clean the dirty surface/platter before you put any food on it.

76B) Rebecca had to soak the surface/platter with soap to get the grease off of it.

77A) We saw the teacher/rooster from across the yard.

77B) She could hear the teacher/rooster on the other side of the wall.

78A) Brenda realized she had left the picture/mascara in her other handbag.
78B) Ken picked up the dropped picture/mascara off the ground and handed it to Pam.

79A) Mary loved her little brother/terrier and was often accused of spoiling him.

79B) Janet took care of Bob's brother/terrier when he went away for the weekend.

80A) All I need is some support/aspirin and then I will be able to finish the project.

80B) Nick asked his roommate for some support/aspirin when he was not feeling well.

81A) Dennis had too much success/tequila very quickly and was not able to handle it.

81B) It was nice of Robert to share his success/tequila with his colleague.

82A) Paul wanted to know how long the process/autopsy would take.

82B) We witnessed the entire process/autopsy being performed by the surgeon.

83A) The boy was brought to the council/dungeon after he had committed his awful crime.

83B) Logan went to see the council/dungeon as soon as he arrived.

84A) Beth wanted to study history/zoology next year at a college in England.

84B) My aunt thought that a degree in history/zoology would be very helpful.

85A) The lady in the red blouse asked the manager/caterer for his number.

85B) Ben wasn't sure if the manager/caterer was prepared for so many people.

86A) Duncan thought that the young student/sparrow was small for his age.

86B) Jane yelled as the student/sparrow fell out of a tree on the playground.

87A) Emma refused to read the chapter/tabloid when I told her what was in it.

87B) Patrick opened up the chapter/tabloid and read it out loud to his wife.

88A) We toured a local company/brewery and wrote a report about it.

88B) I heard that the company/brewery made a large profit this past year.

89A) Before the guests arrived, the kitchen/armoire needed to be cleaned.

89B) The girl searched the kitchen/armoire for the missing candle holder.
90A) For such an expensive restaurant, the service/cuisine is surprisingly bad.

90B) I enjoyed the great service/cuisine at the Indian restaurant.

91A) Sam decided that the village/hammock was his favourite part of the trip.

91B) Ralph decided to rest in the village/hammock before he started on his journey.

92A) The boy was confused by the problem/anagram and had to ask for help.

92B) There was a challenging problem/anagram on the test.

93A) We were unable to repair the damaged marriage/ligament even though we tried.

93B) I was sad to hear that my aunt's marriage/ligament could not possibly be fixed.

94A) Valerie needed to get some material/scissors before she could start the project.

94B) Please bring me the material/scissors and a thread and needle right away.

95A) My father loved his business/vocation and always looked forward to going to work.

95B) After college, Lynn did well with her new business/vocation and made a good salary.

96A) Betty says that she hates children/broccoli but I am not sure if I believe her.

96B) Fiona stopped to pick up the children/broccoli after she got out of work.

97A) The actor ended his monologue with an unexpected question/flourish that made us laugh.

97B) The boy's bizarre question/flourish took everyone in the audience by surprise.

98A) They closed off the dangerous building/catacomb and refused to let anyone enter.

98B) We took a tour of a famous building/catacomb while we were on holiday in Paris.

99A) He admired his father's religion/humility very much.

99B) At a young age, I learned that religion/humility was very important.

100A) I found the research/abstract interesting and wanted to read more about the experiments.

100B) The young man's research/abstract was submitted to an important journal.

101A) Peter said that the painful argument/splinter caused him much distress.
101B) I told Beatrice about the argument/splinter to see if she could help.
102A) Billy said that the extensive practice/tutorial helped him get a good grade on the test.
102B) Melanie attended the lengthy practice/tutorial in the afternoon.
103A) Sue discovered an unknown language/dinosaur while she was in Africa.
103B) My uncle studies a particular ancient language/dinosaur that was common in Asia.
104A) We followed the specific approach/protocol preferred by our boss.
104B) I was taught the preferred approach/protocol for dealing with customers.
105A) When I first arrived in the city, the community/publicist was very helpful.
105B) When the announcement was made, the community/publicist was shocked.
106A) After the boy was caught stealing erasers, the principal/caretaker yelled at him.
106B) He was hired to be the principal/caretaker at the new academy.
107A) I read a book about a useless character/scoundrel who no one liked.
107B) My uncle is a strange character/scoundrel with lots of unusual habits.
108A) It was difficult for the secretary/mercenary to find work.
108B) He needed to find a secretary/mercenary to help with the assignment.
109A) Jeremy received his education/doctorate from a very prestigious university.
109B) Chris finished his education/doctorate and then found a good job.
110A) The man looked up from the newspaper/parchment when his son came into the room.
110B) Because it was so old, the newspaper/parchment had to be handled very carefully.
111A) The man shared his knowledge/portfolio with the other employees.
111B) Margaret was certain that her knowledge/portfolio was a source of envy.
112A) Michael's strange situation/moustache was the topic of many conversations.
112B) Ken was so embarrassed by his situation/moustache that he refused to see guests.
113A) We wanted to get his attention/autograph but he did not see us waiting.
113B) I was glad to get her attention/autograph after the show ended.
114A) The sudden sound of her roommate's telephone/accordion woke Valerie up from her nap.
114B) Barbara hated her neighbor's loud telephone/accordion and bought some earplugs.
115A) Tina witnessed the clumsy president/ballerina tripping on the stairs.
115B) Kathy did not like the snobby president/ballerina and told everyone how she felt.
116A) My aunt told me that I could be a famous professor/astronaut when I get older.
116B) I had a great deal of respect for the professor/astronaut who spoke in my class.
117A) Grant didn't go to the conference/dealership because he was too tired.
117B) John bumped into Nancy at the conference/dealership on Saturday.
118A) Mary asked the department/pharmacist to recommend a possible solution.
118B) Rachel went to the department/pharmacist for help.
119A) The war lasted so long that the government/commandant began to lose hope.
119B) Everyone was surprised when the government/commandant ordered an invasion.
120A) The scholarship was created by a generous individual/benefactor from the private sector.
120B) We honoured the individual/benefactor who funded the new wing in the hospital.