

The Return-Sweep in Reading

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A thesis submitted in partial fulfilment of the requirements of Bournemouth
University for the degree of Doctor of Philosophy

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BOURNEMOUTH UNIVERSITY

Abstract

FACULTY OF SCIENCE AND TECHNOLOGY

Psychology

Thesis for the degree of Doctor of Philosophy

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Return-sweeps are saccadic eye movements that take a reader's fixation from the end of one line to the beginning of the next. Our current understanding of return-sweeps is limited to a description of their physical characteristics. Moving beyond these descriptive characteristics, this thesis examined how lexical processing is influenced by return-sweep execution in both adults and children.

Following a review of the existing eye movement literature in chapter 1, chapter 2 examined the basic characteristics of return-sweep saccades. The reported data indicates that return-sweeps follow one of two trajectories: they land close enough to their target to enable readers to begin a rightwards pass or they are followed by a corrective saccade towards the left margin. When return-sweeps are accurate, the resulting line-initial fixation is longer in duration than intra-line reading fixations. Undersweep-fixations, those preceding corrective saccades, are shorter in duration than intra-line reading fixations. Chapter 3 examined a candidate explanation for longer accurate line-initial fixations; that binocular coordination processes are responsible for inflated fixation times following a return-sweep. Yet, the reported data lend no support for such an account. Instead, it is argued that longer line-initial fixations result from a lack of parafoveal preprocessing.

Chapter 4 directly examined the influence of return-sweep execution on lexical processing at the very start of the line. The studies detailed within chapter 4 indicate that when readers land accurately, lexical processing continues as it would during a left to right reading pass. However, when readers make an undersweep-fixation, they appear able to extract information from the word to the left of fixation such that reading times are shorter on line-initial words following an undersweep-fixation compared to cases in which they are fixated directly after a return-sweep. Chapter 5 further reflects readers' ability to extract information at the point of an undersweep-fixation as indexed by increased skipping rates and reduced gaze

durations for words receiving an undersweep-fixations during a subsequent rightwards pass. Together, these findings challenge the widely held view that undersweep-fixations are uninvolved in lexical processing.

Chapter 6 examined return-sweep saccades in developing readers. Relative to adults, children appear to fixate more extreme positions on a line when reading for comprehension. This likely reflects their reliance on foveal processing to encode written information. Furthermore, like adults, children appear able to extract information at the point of, and to the left of, an undersweep-fixation.

Collectively, the findings from this thesis characterise return-sweep saccades in both skilled and developing readers and consider the implications of return-sweep execution on lexical processing. Generally, it seems that readers continue processing information at the start of the line as they do when reading from right-to-left, except they must wait until this information becomes available in (para)foveal vision as it is unavailable for preprocessing.

Thesis Structure

This thesis conforms to an ‘integrated thesis’ format in which chapters (chapters 2–6) consists of articles written in a style that is appropriate for publication in peer-reviewed journals. The initial and final chapters present an introduction and discussion of the field of research undertaken. The articles included in this thesis are at various stages of the publication/review process, and the status of each paper is summarised below. The main text in each chapter is presented as exact replications of the submitted manuscript and inevitably, there is some repetition as a consequence.

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Status of Articles from this Thesis

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Authors Declaration

I hereby declare that the work presented in this thesis has not been and will not be, submitted in whole or in part to another University for the award of any other degree.

Signature:

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The Return-sweep in Reading
Chapter One
Introduction and Theoretical Background

Over the last five decades, much has been learned about the processes involved in natural reading by examining reader's eye movements (Liversedge & Findlay, 2000; Rayner, 1998, 2009a). However, more is known about eye movements occurring within a line of text than those spanning line boundaries. Eye movements that move a reader's fixation between lines are called "return-sweeps". Return-sweeps precede or follow approximately 20% of all fixations (Rayner, 1998). The prevalence of return-sweeps during natural reading is best highlighted when considering an example. The first page of J. K. Rowling's novel *Harry Potter and the Philosopher's Stone* requires readers to make 30 return-sweeps (excluding any re-reading). This equates to approximately 6,500 return-sweeps for the 233 pages in the 1997 Bloomsbury paperback edition. Despite their prevalence in natural reading, return-sweeps are routinely excluded from eye movement data analysis and model simulations (see Table 1). By excluding these data points, our current understanding of such eye movements is largely limited to a description of their physical characteristics. We know that return-sweeps typically land short of the start of a new line and are followed by a second corrective leftward saccade that brings the eyes to the line-initial word (Hofmeister, Heller, & Radach, 1999). Yet we know very little about how lexical processing is influenced by return-sweep execution. Thus, without further empirical investigation of return-sweep saccades, our understanding of these specific, regularly occurring eye movements during reading will be far from comprehensive.

Table 1.1. Examples of authors choosing data trimming procedures that exclude return-sweep saccades and fixations from analysis.

Authors	Quote
Hand, Miellet, O'Donnell, and Sereno (2010)	<i>"Data were additionally eliminated if...the fixation on the target was either the first or last fixation on a line."</i>
Hand, O'Donnell, and Sereno (2012)	<i>"Data were additionally eliminated if...the fixation on the target was either the first or last fixation on a line."</i>
Kuperman, Dambacher, Nuthmann, and Kliegl (2010)	<i>"...we excluded fixations that landed on the first or the last word of a line or of a sentence for compatibility with other data sets and to avoid the potential influence of the eye movement behaviour at line breaks."</i>
Miellet, Sparrow, and Sereno (2007)	<i>"In accordance with E-Z Reader 7, the first and last words of each line of text were excluded from the simulation."</i>
Pynte and Kennedy (2006)	<i>"The first word in each line was thus excluded from the data set"</i>
Rayner, Slattery, Drieghe, and Liversedge (2011)	<i>"Return sweeps from the first to the second sentence that landed on or beyond the target word were also excluded from analysis."</i>
Reichle, Pollatsek, and Rayner (2006)	<i>"We also excluded the first and last words of each sentence because the first and last fixations are often anomalous due to factors that are unrelated to normal reading"</i>
Whitford and Titone (2012)	<i>"Following prior work ... words at the beginning and end of every line of text were removed from analyses."</i>
Whitford and Titone (2014)	<i>"We excluded words at the beginning and end of every line of text"</i>
Henderson, Luke, Schmidt, and Richards (2013)	<i>"...fixations could not be followed within 700 ms by a return sweep."</i>

It will become clear from the review of the literature below that many findings from the non-reading literature apply to the study of eye movements during reading. This is particularly true for the study of return-sweeps where secondary corrective saccades are likely determined on the basis of similar heuristics between tasks. It is for this reason that the remainder of this chapter begins with a summary of eye movements during non-reading tasks. Several benchmark findings from the reading literature are then discussed. The section that follows will review the basic

characteristics of return-sweep saccades and the adjacent fixations. This section will contextualise studies that have investigated eye movements during non-reading and reading tasks within the current research framework. As no discussion of eye movements in reading would not be complete without reference to computational models of eye movement control, ways in which current modelling efforts could be applied to the study of return-sweeps are discussed in the penultimate section. This chapter closes with the specific aims and research questions under investigation in this thesis.

1.1. Background information on eye movements

The two defining features of eye movements are the eye movements themselves (*saccades*) and the pauses that separate them (*fixations*). Saccades are fast, ballistic eye movements of up to 500° per second. Because of the velocity at which saccades move, humans do not typically encode visual information during a saccade (Uttal & Smith, 1968). As a result of information sampled at the very start and end of a saccade masking visual input during a saccade, blur is not perceived (Brooks, Impelman, & Lum, 1981; Campbell & Wurtz, 1978; Chekaluk & Llewellyn, 1990). The reduced sensitivity to visual stimuli is termed saccadic suppression (Matin, 1974). Despite a lack of encoding during a saccade, cognitive processing does continue (Irwin, 1998; Irwin & Carlson-Radvansky, 1996).

Eye movements take time to plan and execute. Saccade latency refers to the time taken to initiate a saccade. It is used synonymously with fixation duration. Fixation durations are typically in the order of 175-200 ms (Becker & Jürgens, 1979; Rayner, Slowiaczek, Clifton, & Bertera, 1983). However, this varies in relation to the nature of the task and information being processed. Saccade duration, or the time taken to move the eyes, varies as a function of the distance travelled by the eyes. A 2° saccade, typical of reading, takes about 30 ms (Rayner, 1978). Given that saccadic eye movements are the result of muscular contractions, they will be prone to error. That is, saccades will on occasion overshoot or undershoot their target (this will be discussed at greater depth in section 1.2.).

Eye movements are essential due to the structure of the human retina. The human retina is comprised of three regions: the fovea, parafovea, and the periphery (Rayner, 1978; Balota & Rayner, 1983). The fovea corresponds to the central 2° of vision. Visual acuity is greatest in this region (Bruce, Green, & Georgeson, 2003;

Findlay & Gilchrist, 2003; Mather, 2006; Snowden, Thompson, & Troscianko, 2006). The parafovea is the region that extends outward from the fovea to 5° either side of fixation and the periphery extends beyond this (Balota & Rayner, 1991). The further away a stimulus falls outside of foveal vision, the less high-frequency spatial detail will be perceived. Thus, to see a stimulus in detail it must be positioned on the fovea. Despite visual acuity limitations in the parafovea, it is possible to extract information in this region (see Schotter, Angele, & Rayner, 2012 for a review).

While it is alluring to believe that eye movement patterns are similar between tasks, this may not be the case. Rayner, Li, Williams, Cave, and Well (2007) demonstrated that reader's patterns of saccades and fixations do not correlate with those measured in scene perception and visual search (but see Henderson & Luke, 2014). This is likely the result of each specific task requiring the use of different cognitive systems which ultimately exert differing influences on the oculomotor system. While the precise pattern of saccades and fixations differ between non-reading and reading tasks, oculomotor processes between tasks are remarkably similar.

1.2. Eye movements during non-reading tasks

In this section, the basic characteristics of saccadic eye movements during non-reading reading tasks are discussed. This will provide readers with information that is sufficient to understand several eye movement patterns typically found in reading, specifically the return-sweep. Across individuals, saccades have a characteristic temporal profile (Gilchrist, 2011). The eye is initially stable and then quickly accelerates towards peak velocity followed by a rapid deceleration and a quick return to stability. The peak velocity that a saccade reaches will be a function of its amplitude— the greater the amplitude, the greater the velocity. A similar relationship exists between saccade duration and amplitude. Under normal viewing conditions, saccades have a very wide range of amplitudes. In scene viewing, saccade amplitudes of 15° are typically observed. This is considerably larger than the 2° observed in reading.

During a fixation, the eyes are not completely still. Three type of miniature eye movements exist during fixations (Carpenter, 1988). These are tremor, drift, and microsaccades. All three types are thought to reduce neural adaptation and prevent fading of the visual image on the retina (Engbert & Kliegl, 2004; Martinez-Conde &

Macknik, 2011; Martinez-Conde, Macknik, & Hubel, 2004). However, a link between covert attention and the generation of microsaccades has been demonstrated (Engbert & Kleigl, 2003; Laubrock, Engbert & Kliegl, 2005).

There is great variability in fixation durations during both non-reading and reading tasks, with right skewed distributions being typical of both. This has typically led researchers interested in fixation durations to transform data so that the distribution approximates a Gaussian distribution (Carpenter & Williams, 1995; Baayen, 2008; but see Lo & Andrews, 2015). The distribution of fixation duration is typically unimodal; however, under some conditions it is possible to observe a distribution of latencies that are faster than normal. These saccades are referred to as express saccades (Fisher & Weber, 1993). Express saccades are typically observed in the non-reading literature, but these are very similar in their characteristics to corrective saccades in reading which move the eyes small distances following a non-optimal landing position.

Fixation durations are influenced by both the requirements of the saccade and the extraction of information at the location at which a fixation occurs. Kalesnykas and Hallett (1994) systematically investigated the influence of the distance from the current fixation point to the target (or eccentricity) on fixation duration. Over a wide range of eccentricities, saccade amplitude had little or no effect on fixation duration. However, small saccades of 1° of visual angle lengthened fixation durations. Visual factors such as decreased intensity (Kalesnykas & Hallett, 1994), decreased contrast and increased spatial frequency of the target (Ludwig, Gilchrist, & McSorley, 2004) lead to longer fixations. Events at the currently fixated location also influence fixation duration. Saslow (1967) demonstrated that when a currently fixated item disappears before the new target appears, fixation durations are shorter. It is generally thought that this effect is observed because the disappearing stimuli results in attentional disengagement and prepares the visual system to initiate a saccade (Forbes & Klein, 1996).

Goal-directed saccades can be accurate or inaccurate. Accurate saccades are those that reach their target while inaccurate saccades undershoot or overshoot their target. Though most saccades tend to be hypometric—they fall slightly short of their intended target (Gilchrist, 2011). Saccades typically undershoot their target by about 10% of the required distance (Becker & Fuchs, 1969; Henson, 1978). In response to

saccadic undershoot, the saccade orienting system often initiates a secondary corrective saccade to position the fovea closer to its intended target (Becker, 1972; Beck & Fuchs, 1969; Carpenter, 1988; Hallet, 1978; Prablenc & Jeannerod, 1975; Weber & Daroff, 1972). Secondary saccades almost immediately after the end of the primary saccade. It has been proposed that such error correction relies on an internal signal (e.g. an efference copy) as visual feedback is not available immediately after the primary saccade. However, other accounts suggest that secondary saccades are visually guided with the initiation of a corrective saccade occurring when the deviation between landing site and the intended target reaches a certain threshold (Becker, 1976). This explanation is able to account for the finding that fixations preceding secondary saccades are shorter in duration when a longer saccade is required (Becker, 1972; Kapoula & Robinson, 1986; Prablanc & Jeannerod, 1975). That is, larger deviations between the target and actual landing positions will be easier to detect than smaller deviations.

With increasing eccentricity, corrective saccades become more frequent (Frost & Pöppel, 1976; Lemij & Collewyn, 1989). Lemij and Collewyn (1989) examined the relationship between corrective saccade latency and target eccentricity. Fixations prior to corrective saccades were shorter for larger target eccentricities. This was independent of the magnitude of the saccadic error. In a more recent investigation of secondary saccades, Ohl, Brandt, and Kliegl (2011) examined the influence of target eccentricity and saccadic error on various corrective saccade parameters. When participants fixated a single dot presented at 6° or 14° of visual angle from a central fixation point, secondary saccades were required on 55% of trials for close targets and 83% of trials for distant targets. Corrective saccade amplitudes were increased for greater saccade error while latencies were reduced. In the far condition, even when error was small, the fixation preceding corrective saccades remained short, indicating that participants were more likely prepared to initiate a secondary saccade in the far condition regardless of landing position. This endeavour indicates that corrective saccade execution is influenced by both saccadic error and characteristics of the preceding saccade.

Ohl, Brandt, and Kliegl (2013) subsequently examined the extent to which secondary saccades are pre-programmed along with the primary saccade. This was achieved by asking participants to saccade between dots presented at 6° or 14° of

visual angle from a central fixation point. When participants crossed an invisible boundary, located at a distance of 2° from the initial fixation point, the target disappeared. This resulted in a blank display from which participants could not gain post saccadic visual feedback. In the absence of post saccadic feedback, secondary saccades were observed following 42% of saccades in the close condition and 50% in the far condition. Furthermore, the latency and amplitude of the secondary saccade was related to the primary saccade error. This led authors to conclude that participants use extraretinal feedback to influence the likelihood of initiating a corrective saccade. Strong evidence for an extraretinal error signal influencing secondary saccade planning comes from the observation that secondary saccades move in a direction to compensate under-/overshoot. Together, Ohl et al. (2011, 2013) provide evidence to suggest that both visual feedback following a saccade and extraretinal information are used to plan and execute corrective saccades,

The studies reviewed generally require participants to saccade between two simple, distinct visual stimuli. However, when distractors appear in close proximity to the target of a saccade, landing positions generally falls somewhere between the target and the distractor. This effect has been termed a global effect (Findlay, 1982). Global effects become more pronounced when targets are embedded within multiple distractors (Findlay, 1997). Typically, initial saccades are made towards the distractors and a subsequent saccade is made towards the target. For instance, when participants were required to search for a target object amongst distractors, Zelinsky, Rao, Hayhoe, and Ballard (1997) reported that the first saccade tended to be directed to a group of objects in the display and subsequent saccades progressively targeted small groups. This indicates that the scale of visual search changed as the search progresses.

The accurate programming of saccades requires a process that responds to consistent landing position error (McLaughlin, 1967). This process of saccade adaptation is important because it allows the system to make accurate motor responses despite changes in the system over time (Optican, 1985). Experimentally this process can be studied by asking participants to generate a saccade to a target and, during the saccade, moving the target a consistent amount either toward or away from fixation. As a result of the target movement, the saccade will either land short of the target or overshoot it. Over a series of trials participants will begin to generate

saccades that adapt to this shift and are once again target directed (Chaturvedi & van Gisbergen, 1997; Chen-Harris, Joiner, Ethier, Zee, & Shadmehr, 2008; Erkelens & Hulleman, 1993; Ethier, Zee, & Shadmehr, 2008; Wallman & Fuchs, 1998).

When engaged in daily activities, including reading, saccades do not occur in isolation—each is separated by a fixation. The sequence of saccades is referred to as a scanpath. Models of saccade generation (e.g. Findlay & Walker, 1999) assume that saccades are programmed separately during the preceding fixation. However, a number of studies have shown that saccades can be planned in parallel. Findings from the double-step paradigm indicate that some saccades have short latencies of less than 100 ms (e.g. Becker & Jürgen, 1979), which is shorter than the 150-200 ms estimate to launch a saccade (Altmann, 2011). It has, therefore, been suggested that saccades may be planned in parallel. For example, McPeck, Skavenski, & Nakayama, (2000) had participants carry out a search task in which they generated a saccade to a target presented with distractors. On some trials the participant's first saccade was erroneously directed to a distractor. When this occurred, the target position was switched during the saccade so that the participant would now generate a saccade towards the target. Following this first saccade, participants sometimes generated a second saccade to the old target position. This suggests that they had detected the target location before the execution of the first saccade and pre-programmed the second saccade to the old target location. Together, these findings at the very least demonstrate that saccades can be programmed in parallel under certain circumstances.

The generation of a saccade to a new location results in a large processing advantage at that location. In the majority of situations, the target for the next saccade has to be selected using the more limited visual information that is available from peripheral vision. Thus, during a fixation a viewer typically processes information at the point of fixation and uses degraded information in the parafovea and periphery to target their subsequent saccade.

In the literature the distinction is often drawn between 'top-down' and 'bottom-up' factors that determine which location within space is selected for the next fixation. A 'bottom-up' signal is one that arises from the visual input and attracts the eyes to that location regardless of the task currently being carried out. For example, a sudden visual onset may result in the eyes fixating that location regardless of the task (Ludwig & Gilchrist, 2002; Theeuwes, Kramer, Hahn, &

Irwin, 1998). A number of models of visual salience have been developed to explain how visual factors may guide the eyes to one location rather than another (e.g. Itti & Koch 2000; Navalpakkam & Itti, 2005). Which location is fixated is also determined by task. This ‘top-down’ control allows the eyes to be directed to locations that are task relevant regardless of their visual salience. Yarbus (1967) showed that when participants viewed pictures the locations that were fixated strongly depended on the task the participants were being asked to carry out. In this case the visual information in the picture remained constant across conditions so any differences between conditions must have been due to task-related or top-down factors. Stimulus and task-related factors combine to determine the target for the next saccade to ensure that the selection of the next saccade is determined by both the salience and relevance of the information at that location (Fecteau & Munoz, 2006; Schall & Cohen, 2011).

In sum, saccades are essential to position the fovea onto the location we wish to process and encode. In the interval preceding a saccade—the fixation—two processes occur simultaneously. Visual information is extracted and the subsequent saccade is planned. The saccade target selection process is always based on degraded visual information because visual processing falls off so dramatically in terms of acuity the further away from the currently fixated location. These two processes impact both when a saccade occurs and where the saccade is directed. From the information reviewed in this section it should be clear that eye movements are tightly linked to the goal of the task. As will become clear in section 1.3., many of these basic characteristics apply to the study of eye movements during reading.

1.3. Eye movements during reading

In this section, the basic characteristic of eye movement during reading are discussed. This section will provide readers with the information necessary to understand the word-level manipulations made throughout this thesis.

For readers of English, the average fixation duration is 225-250 ms (see Rayner, 1998, 2009a; Schotter & Rayner, 2015). The average saccade is 7-9 characters in length (Rayner, 1998, 2009a), with most saccades moving from left-to-right. However, two types of right-to-left movements occur during English reading: return-sweeps and regressions. Return-sweeps move the point of fixation from one line to the next. Usually, return-sweeps are initiated from within the last 5-7

characters of the current line and land within first 5-7 characters of the next line (Rayner, 1998; see section 1.3.4). Regressive eye movements refixate previously fixated material. Most regressive eye movements are likely to occur within words and act to refixate when viewing is non-optimal (Reichle et al., 2013). However, regressions also occur between words as a result of disruption in lexical, syntactic, or semantic processing. Thus, regressions are related to processing difficulty (Rayner, 1998; Rayner & Pollatsek, 1989). Additionally, regression rates are increased when text is conceptually difficult and when readers are less skilled (Blythe & Joseph, 2011; Clifton & Staub, 2011; Rayner, 1998, 2009a; Rayner, Chace, Slattery, & Ashby, 2006).

1.3.1. Eye movement measures and gaze-contingent paradigms during reading

Eye-trackers have made it possible to track the pattern of saccades and fixations made by readers to a high degree of temporal- and spatial-accuracy. Eye-trackers are capable of sampling the position of the eye once per millisecond while participants read text from a monitor. The durations of reader's fixations can be used to index the level of cognitive processing that readers engage in during the reading of linguistic materials. When a manipulation of the text influences measures such as first-fixation duration (see Table 1.2.), the manipulation is considered to have a relatively early influence on cognition (e.g. encoding), whereas a variable that influences only total viewing time is considered to have a late effect (e.g. integration).

Saccade targeting measures are also an indication of word processing. For instance, word skipping reflects the decision to fixate the upcoming word. Saccade length and fixation locations within words are examples of saccade targeting measures. These measures are primarily driven by visual qualities of the text whereas fixation durations are largely influenced by linguistic properties of the text. Thus, it would appear that the processes controlling saccade targeting measures (*where* to move the eyes) and fixation durations (*when* to move the eyes) are independent (Rayner & McConkie, 1976; Rayner & Pollatsek, 1981). The factors influencing the decision of when and where to move the eyes will be discussed in greater detail in section 1.3.2. The remainder of this section will focus on eye-trackers and their capabilities.

Table 1.2. Eye movement measures typically reported in eye movement studies.

Measure	Definition and Time Course
First-fixation duration	<i>An early measure, defined as the duration of the first first-pass fixation on a target word.</i>
Single fixation duration	<i>Also an early measure, defined as the duration of the first-fixation on a word that receives only one fixation.</i>
Gaze duration	<i>The sum of all first-pass fixations on the target word during first-pass reading.</i>
Skipping rate	<i>The percentage of instances where a word is not fixated during first pass reading. This reflects the earliest stages of word processing, where a decision to fixate or skip the upcoming word is made.</i>
Regression rate	<i>A late measure recorded in later stages of processing. Measures the percentage of regressions in or out of the target.</i>
Second pass duration	<i>A late measure recorded in the later stages of processing. Measures the time duration spent re-reading a target word after first-pass.</i>
Total viewing time	<i>A late measure of processing. Measures the sum of the time spent reading a target word during first and subsequent passes.</i>

Note. Based on Clifton, Staub, & Rayner (2007) and Juhasz and Pollatsek (2011).

The accuracy at which eye-trackers sample eye movements has enabled the implementation of several gaze-contingent paradigms. During gaze-contingent paradigms, eye-trackers use the current position of the eyes in order to alter the visual information displayed to participants. These techniques have provided several benchmark findings which have led to the development of sophisticated models of eye movement control during reading.

The first of these gaze-contingent paradigms is the moving window paradigm (McConkie & Rayner, 1975). In this paradigm, the text outside of a predetermined window size is altered in some way (e.g. masked with strings of Xs) while the information inside of this window is unaltered. When a saccade is made from one location to the next, a display change occurs so that the window of text moves contingent on the fixation (see Figure 1.1). This technique provides an estimate of the perceptual span or how much information readers extract across fixations. The perceptual span is determined by the size of the smallest window for which reading

occurs at a normal rate. For skilled English readers, the perceptual span extends 3-4 characters to the left of fixation and 14-15 characters to the right (McConkie & Rayner, 1975; McConkie & Rayner, 1976). Subsequent variations of the moving window paradigm which compensate for acuity limitations in parafoveal vision indicate that the perceptual span remained 14-characters to the right of fixation. This suggests that the perceptual span is determined by attention and ongoing processing constraints (Miellet, O'Donnell, & Sereno, 2009).

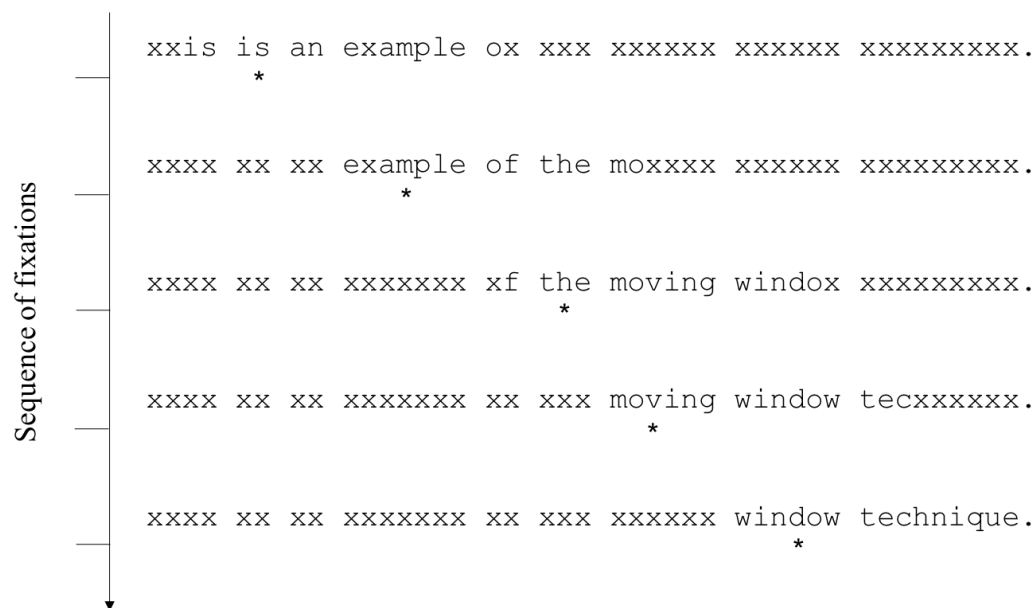


Figure 1.1. The moving-window paradigm, in which a sequence of five fixations is represented in five rows of the figure (the position of each fixation is denoted by an Asterix). Letters outside of the window are distorted with Xs. Reading times and eye-movement behaviour are examined across different window sizes (here, a window of 3 characters to the left and 14 to the right is represented) and compared against normal reading, in which the entire sentence is continuously visible, to determine the window size at which measures of reading behaviour match that under normal conditions. This figure was adapted from Blythe (2014).

A second type of gaze-contingent technique is the boundary change paradigm (Rayner, 1975). In this paradigm, an invisible boundary is placed left of the target word. Prior to the eye crossing the boundary, a preview string is presented in the location of the target word (see Figure 1.2). In the control condition, the preview is the actual target word (valid preview) while in the experimental condition, the preview contains at least some different letters to the actual target word (invalid

preview). When readers make a saccade across the boundary, the preview word is replaced with the target word. Implementations of this paradigm have shown that with a valid preview, readers' fixation times are shorter on that word than when an invalid preview is shown. This advantage is known as the preview benefit. The preview benefit strongly indicates that readers extract and process information about the preview string prior to direct fixation.

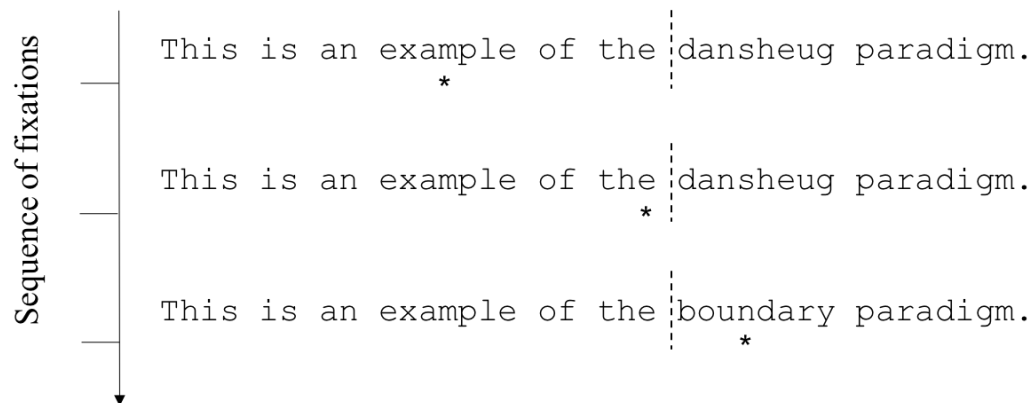


Figure 1.2. The boundary paradigm, in which a preview letter string initially appears on the screen in place of a prespecified target word (Rayner, 1975). A sequence of three fixations is shown (each fixation denoted by an asterisk). An invisible boundary (represented here by the dashed vertical line) is placed in front of the target location, and the preview letter string is replaced with the correct target word during the first saccade that crosses the boundary. This figure was adapted from Blythe (2014).

The preview benefit has been explained with reference to the allocation of attention to parafoveal word(s) (see Schotter et al., 2012 for a detailed review). It is generally assumed that attention is directed towards the saccades target (e.g. Deubel & Schneider, 1996; Rayner et al., 1978). This suggests that the preview benefit will only be observed for the location of the saccade. To examine this prediction, McDonald (2006) had participants read text where a boundary change could occur at the position of the saccade target or after the target of the saccade. This was achieved by placing the invisible boundary that would trigger a change in word $n+1$ to be either at the end of a 7-letter word or near the centre of a 7-letter word. Because word n would often require a refixation, the saccade to the end of word n would trigger the near centre boundary change. When a refixation saccade took the eye across the boundary in the near centre condition, no reliable effect of preview

validity was observed. When the boundary was placed just after the pre-target word, a clear preview benefit effect was observed. This strongly indicates that the processing advantage for a valid preview holds only if it is the target of the immediately preceding saccade. It would also appear that pre-processing of words in the perceptual span is fixation based and there is little evidence that this builds across fixations.

Interestingly, the amount of information that readers can acquire in parafoveal vision is influenced by the processing difficulty of the currently fixated word. Words considered difficult to process are considered to have a high foveal load. That is, the processing demands of the currently fixated word may modulate the extent to which the upcoming word is preprocessed (Henderson & Ferreira, 1990; White, Rayner, & Liversedge, 2005). Indeed, Henderson and Ferreira have shown that preview benefit effects exist only when foveal load was low (i.e. a high-frequency word). White et al. (2005) and Angele, Slattery, and Rayner (2016) have also reported parafoveal processing is modulated by the frequency of the foveal word.

While the above outlined gaze-contingent techniques manipulate the availability of parafoveal information, two gaze-contingent techniques have been used to investigate foveal processing. Using such a technique Rayner and Bertera (1979) highlighted the importance of foveal processing during reading. In their study, a visual x-string masked foveal vision and moved contingent with participants point of fixation (see Figure 1.3). With no mask, participants read 332 words per minute (wpm). When a single letter in a word (the letter at the point of fixation) was masked, participants read, on average, 165 wpm. When the mask occluded three- and five-character spaces around fixation, reading rates dropped dramatically. The average reading rate was 55 wpm in the 3-letter condition and 42 wpm in the 5-letter condition. When participants were asked to report what they had read, participants often reported incorrect versions of this sentence. For example, the sentence “The pretty bracelet attracted much attention” was read as “The priest brought much ammunition”. This study demonstrates that foveal processing is essential for correct word identification.

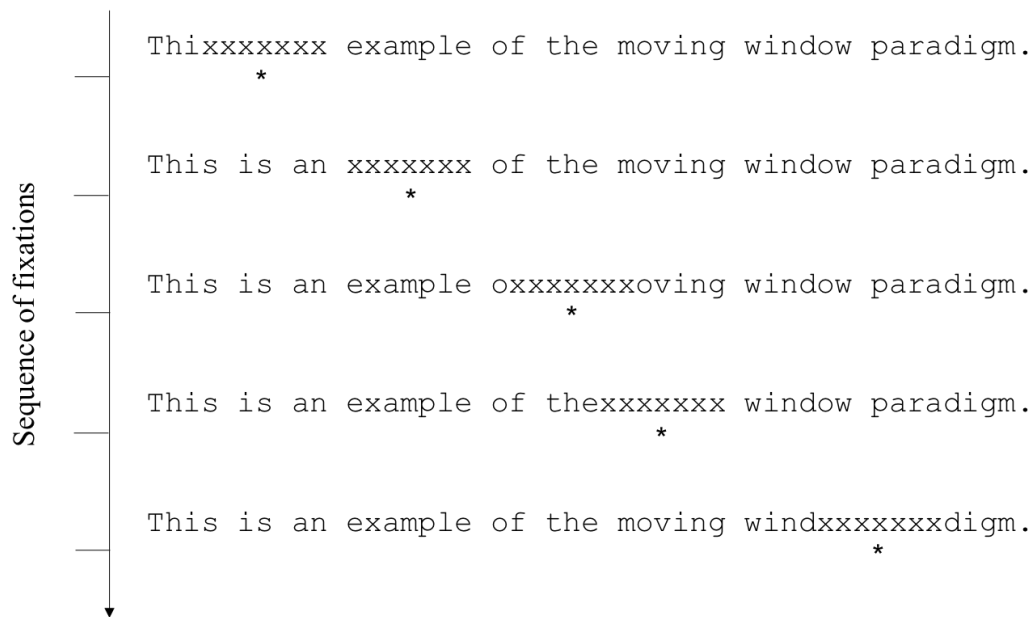


Figure 1.3. The moving-window paradigm in which a 7-character foveal mask appears around the point of fixation. A sequence of five fixations is represented in five rows of the figure (each fixation is denoted by an Asterix). Letters within the window are distorted, typically being replaced with Xs. This figure was adapted from Blythe (2014).

The second gaze-contingent technique implemented to investigate foveal processing is the disappearing text paradigm (Liversedge et al., 2004; Rayner, Liversedge, & White, 2006; Rayner, Liversedge, White & Vergilino-Perez, 2003). In this paradigm, each fixated word disappears (or is masked) some interval after fixation onset (e.g. 60 ms; see Figure 1.4). The word remains invisible until reader's gaze leaves that word. As a result, readers have 60 ms to encode and extract the visual information that is necessary to identify it before it is no longer available in foveal vision. Experiments using this paradigm have revealed that within 40-60 ms, skilled adult readers can read the text at a normal rate with few disruptions in comprehension (Liversedge et al., 2004; Rayner, Yang, Castelano, & Liversedge, 2011; Rayner et al., 2006). This indicates that readers encode the visual information necessary for visual processing very rapidly during a fixation.

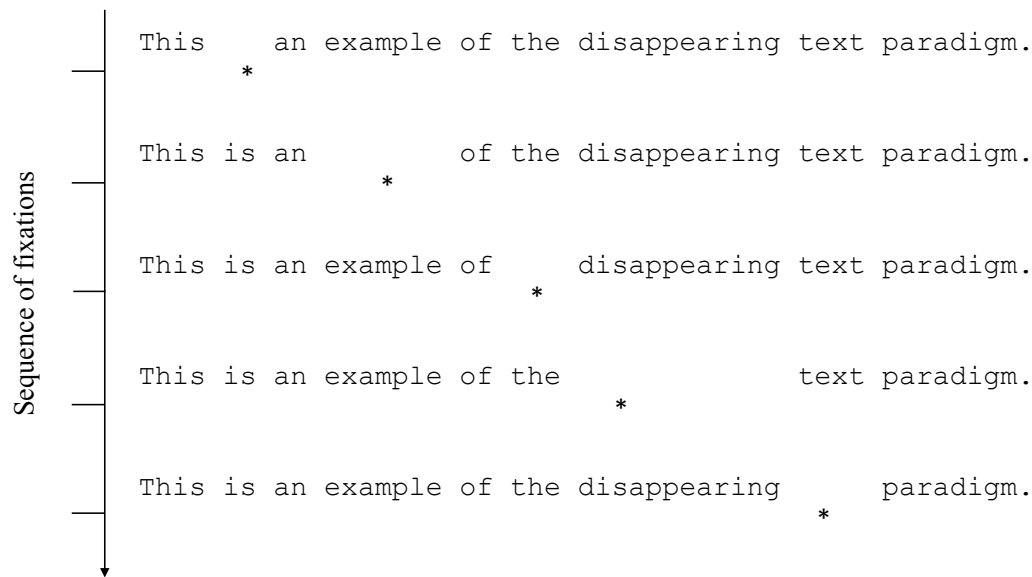


Figure 1.4. The disappearing-text paradigm, in which each word disappears at a predetermined interval once it is fixated but then reappears once the eyes move to another word within the sentence. Here, a sequence of fixations on a sentence is represented (each fixation is denoted by an asterisk under the text). This figure was adapted from Blythe (2014).

1.3.2. The control of eye movements during reading

As indicated in section 1.2., there are two components to eye movement control. These are the *what* and *where* components. Rayner and McConkie (1976) reported that there is typically no correlation between how far the eyes move and the duration of a given fixation. This evidence suggests that these two decisions are relatively independent. Accordingly, these two topics are discussed separately.

1.3.2.1. Determinants of fixation locations during reading

Saccade targeting is largely driven by visual features of the text, such as word length. Saccade length is influenced by the length of the fixated word and the word to the right of fixation. Word length properties on the fixated word and the parafoveal word to the right of fixation influence saccade length (Inhoff, Radach, Eiter, & Juhasz, 2003; Juhasz et al., 2008; Rayner, 1979; White et al., 2005). When the parafoveal word is long or very short, the saccade out of the foveal word will be longer than if it were of a medium length. This is because readers will be able to fully process a short word in parafoveal vision and programme a skip of that word. Saccades will be longer for longer words as readers will target a more central location to afford better lexical processing. It is also clear that spaces between words are used to segment the text and target where a saccade will land (for a review see

Rayner, 2009a). When participants were presented with compound words presented together (*softball*) or presented with a space (*soft ball*), Juhasz, Inhoff, and Rayner (2005) reported that fixations landed further into un-spaced compound words. Below the factors influencing whether a word is fixated and the landing position within a word are reviewed.

1.3.2.1.1. Skipping effects

One-third of words do not receive direct fixation during reading and are skipped (Brysbaert, Drieghe, & Vitu, 2005). The decision to skip a word is made based upon the information available to a reader in parafoveal vision. Word length is the strongest predictor of word skipping (Brysbaert et al., 2005; Drieghe, Brysbaert, Desmet, & De Baecke, 2004; Drieghe, Desmet, & Brysbaert, 2007; Rayner, 1998). Vitu, O'Regan, Inhoff, and Topolski (1995) reported that 40% of 3-letter words were fixated, whereas 70% of 5-letter words were fixated. When two short words occur in succession, they are both likely to be skipped. Short words preceding content words are also frequently skipped (on approximately 66% of occasions; Drieghe, Pollatsek, Staub, & Rayner, 2008; Gautier, O'Regan, & LaGargasson, 2000). It is not clear whether it is a word's length in letters or its horizontal extent that contributes to such an effect. Hautala, Hyönä, and Aro (2011) presented evidence to suggest that the latter of these possibilities is most likely to determine word skipping. Hautala et al. presented a 4- or 6-letter target word in a sentence, while varying font so that the words of different lengths subtended the same or different amounts of visual angle. They reported that 4-letter words were skipped more often than 6-letter words when they subtended a smaller visual angle, but skipped a similar amount when they subtended the same visual angle.

The influence of linguistic factors such as frequency and predictability have also been examined on word skipping. Brysbaert et al. (2005) reported that high-frequency words were skipped 16% of the time while skipping rates for low-frequency words were 11%. This frequency effect is also dependent on the length of the target, with a difference of 10% for 5-letter words and 4% for 7-letter words (Rayner & Fischer, 1996). Brysbaert et al. also reported that skipping rates were 8% higher for words that were predictable given their prior context. Evidence suggests that the effect of predictability on word skipping is rapid. Furthermore, Fitzsimmons and Drieghe (2013) reported that skipping rates did not differ for target words that

became predictable as a result of a single preceding word compared to those that gradually became predictable across the sentence.

1.3.2.1.2. Landing position effects

Fixation locations within words appear influenced almost exclusively by visual and oculomotor factors. Readers appear to use word length information in parafoveal vision to target the centre of words. Word centres are targeted as this is where word identification processes appear optimal (known as the optimal viewing position, OVP; Nuthmann, Engbert, & Kliegl, 2005; O'Regan & Lévy-Schoen, 1983; Vitu, O'Regan, & Mittau, 1990). When fixations occur further from word centres, refixations occur at an increased rate (O'Regan, Lévy-Schoen, Pynte, & Brugailière, 1984; Rayner et al., 1996; Vitu et al., 1990). Additionally, non-optimal viewing locations are associated with increased fixation durations in studies of isolated word recognition (O'Regan et al., 1984). In general, landing positions within words tend to follow a normal distribution centred at a position slightly to the left of the word centre (Rayner, 1979). This modal position has been termed the preferred viewing location (PVL; McConkie, Kerr, Reddix & Zola, 1988; McConkie, Kerr, Reddix, Zola, & Jacobs, 1989; Vitu et al., 1990).

Readers' initial fixations within words appear driven by word length, with fixations landing closer to the centre of short compared to long words (e.g., Bertram & Hyönä, 2003). This is despite the tendency for readers to make longer saccades to reach the centre of long words (e.g., Hautala et al., 2011). Initial landing positions within words are influenced by the distance between the saccade launch site and its distance from the centre of the targeted word. McConkie et al. (1988) reported that readers tended to overshoot word centres when making saccades less than 7 characters in length. In contrast, readers tended to undershoot word centres when making saccades longer than 7 characters. Thus, when the saccade target is far away, the initial fixation on a word will be further to the left of the centre. McConkie et al. attributed their observations to saccadic range error, whereby readers show a bias for making saccades of a certain length. In addition to saccadic range error, random error will influence saccade landing position. This is influenced by the length of the saccade (McConkie et al., 1988).

The orthographic characteristics of the upcoming word influence reader's landing position within that word. Unusual orthographic sequences at the start of an

upcoming word (e.g. avbivist vs activist) result in initial fixations landing towards the start of the word (Plummer & Rayner, 2012). While visual orthographic information appears to influence saccade targeting, higher-level non-visual factors such as word frequency (Rayner et al., 1996) and predictability (Rayner, Binder, Ashby, & Pollatsek, 2001) do not.

In summary, readers' initial fixations within words are primarily determined by visual factors. While effects of frequency and predictability on the decision to fixate an upcoming word appear modest, the effects of length and launch site are much stronger. Visual factors appear to almost exclusively influence initial fixation positions within words, with linguistic aspects of the text having very little influence. What is rather less clear is whether return-sweep targeting is influenced by the variables. Given that readers return-sweeps will be targeted to a location in peripheral vision, it is unlikely that linguistic properties of the word are acquired and inform targeting.

1.2.3.2. Determinants of fixation durations during reading

A number of visual and linguistic factors influence fixation durations during reading, though for brevity's sake, only those of relevance to understanding this thesis discussed here (see Rayner, 1998 for a wider review). The subsequent subsections will provide an overview of how lexical properties of the word and the reader determine the duration of fixations. In empirical chapters, these determinants will be reviewed at greater depth in relation to specific research questions.

1.2.3.2.1. Word frequency effects on fixation durations

The frequency with which a word appears in printed text (i.e. its number of occurrences per million words, e.g. Brysbaert & New, 2009) is an important proxy measure for processing difficulty. Effects of word frequency demonstrate the sensitivity of eye movements to the linguistic properties of the text. When word length is controlled, low-frequency words receive longer fixation durations relative to high-frequency words (Altarriba, Kroll, Scholl, & Rayner, 1996; Henderson & Ferreira, 1990; Inhoff & Rayner, 1986; Rayner & Duffy, 1986; see also Pollatsek, Juhasz, Reichle, Machacek, & Rayner, 2008; Reingold, Yang, & Rayner, 2010; Reingold, Reichle, Glaholt, & Sheridan, 2012; Staub, White, Dreighe, Holloway, & Rayner, 2010; see Rayner 1998 for an extensive review).

Though frequency effects have been found across multiple studies, it is important to differentiate between the techniques used to investigate such effects. In controlled experiments, frequency effects are examined by varying a single target word in a sentence frame. Participants typically read a number of items in which a high- or low-frequency target word is embedded. The manipulation of a single target word enables researchers to control for other word-based variables. The word *chest* is high-frequency in the following sentence while the word *trunk* is low-frequency.

(1) *Mary bought a chest/trunk despite the high price.*

In the case of this specific example, participants tend to fixate the low-frequency word (*trunk*) for more time than the high-frequency word (*chest*; Henderson & Ferreria, 1990). Due to the controlled nature of experimental design, it is possible to conclude that an effect was the result of the variable being manipulated.

Corpus studies have also been conducted to examine frequency effects (Kliegl, Grabner, Rolfs, & Engbert, 2004). In corpus studies, participants read large amounts of text that have not been manipulated in a specific way. Readers' fixations on each word are then analysed with various characteristics of that word entering analysis. By this method it is possible to determine the factors which significantly influence fixation times. While it is perhaps more difficult to assume that an effect solely results from the items included in the analysis, this analysis technique does provide substantial statistical power, as each word is analysed rather than a single word per item. With reference to frequency effects, Kliegl et al. (2004) observed the robust finding that as frequency increased, fixation times decreased for those words.

What is perhaps most interesting is that, in the disappearing text paradigm, word frequency effects remain even when a word is no longer visible. That is, when a target disappears at 50-60 ms post fixation onset, the fixation in that location still varies as a function of the word frequency with low-frequency words still receiving longer fixations (Blythe et al., 2009; Liversedge et al., 2004; Rayner et al., 2003, 2006, 2011). Together, these findings present the strong evidence to support the conclusion that cognitive processing associated with the fixated words determine when the eyes will move.

1.2.3.2.2. Word predictability effects on fixation durations

The predictability of a word from its preceding context has a strong influence on fixation duration. The word *coffee*, is predictable in the following sentence:

(1) *John is grumpy before he's had his morning coffee.*

In the following sentence, the word *shower* would be less predictable, although it remains plausible within the sentence context:

(2) *John is grumpy before he's had his morning shower.*

Target word predictability is typically assessed via a cloze norming procedure (Taylor, 1965). In this task, participants are presented with a sentence up until a critical target word (e.g. *John is grumpy before he's had his morning _____*). Based on the preceding sentence, participants are then asked to produce a word that they feel is likely to come next. Targets that are predictable (e.g. *coffee*) are generated more in the cloze procedure than those that are non- or low-predictable (e.g. *shower*).

Relative to unpredictable words, highly predictable words are recipients of fewer, shorter fixations and receive fewer refixations during sentence reading when word length is controlled (see e.g. Balota et al., 1985; Binder, Pollatsek, & Rayner, 1999; Dreighe et al., 2004; Erlich & Rayner, 1981; Rayner et al., 2001; Rayner, Slattery, Dreighe, & Liversedge, 2011; Rayner & Well, 1996). The emergence of predictability effects in the earliest possible eye movement measures (word skipping, first-fixation duration) indicates that a word's predictability influences visual word recognition. When the temporal relationship between predictability and word frequency is considered, both variables act at an early stage of processing. Survival analyses indicate that divergence points for predictability occur at 140 ms (Sheridan & Reingold, 2012) which is comparable to the frequency divergence point of 145 ms (Reingold et al., 2012). These results are consistent with event-related potentials studies that have demonstrated both word frequency and predictability effects during the N1 component, from 132-192 ms post-stimulus onset (Sereno, Brewer, & O'Donnell, 2003).

Given that both frequency and predictability influence skipping rates and early eye movement measures, it has been proposed that these two lexical variables would have an interactive effect on fixation duration. That is, the cost of processing a low-frequency word should be eliminated when the word is made predictable. Yet, there is no strong evidence of an interaction on eye movement fixation duration measures of reading (Slattery, Staub, & Rayner, 2012). Instead, the majority of eye movement studies report additive effects of frequency and predictability on fixation times (Altarriba et al., 1996; Ashby, Rayner, & Clifton, 2005; Kennedy, Pynte,

Murray, & Paul, 2013; Miell et al., 2007; Rayner et al., 2004; Rayner, Binder, Ashby, & Pollatsek, 2001; Slattery et al., 2012; Whitford & Titone, 2014). Thus, based on an additive factors logic (Sternberg, 1969), frequency and predictability are influencing independent mechanisms of word recognition. However, this picture is complicated by the fact that interactive effects have been reported in word skipping (Gollan et al. 2011; Hand et al. 2010; Rayner et al. 2004). Given that these studies report effects in different directions, there is little justification for concluding that frequency and predictability jointly impact word skipping.

1.2.3.2.3. Word length effects on fixation durations

The length of a word strongly influences how long readers spend processing it. Longer words have more constituent letters. This results in readers making multiple samples of a long word in order to process increased visual and lexical information. Thus, longer words are fixated for longer (e.g. Kliegl et al., 2004; Pollatsek et al., 2008; Rayner et al., 1996). Though this effect often results from refixations on longer words as opposed to longer single fixations. While word length effects are consistent in their influence on how long the reader fixates a word, it arguably has a stronger influence on where the reader moves their eyes rather than for how long (see section 1.3.2.1).

1.2.3.2.4. Readers' characteristics on fixation durations

While lexical characteristics of the fixated word influence eye movements during reading, characteristics of the individual also influence their patterns of saccades and fixations during reading. This section introduces some of the skill-related differences in reader's eye movements with particular emphasis on developing readers.

Until relatively recently, there has been a paucity in research examine children's eye movements (see Blythe & Joseph, 2011 for a detailed discussion). However, studies that have been conducted with children thus far are very consistent in their findings. Compared to adults, children read at a slower rate, they make more and longer fixations (Blythe, 2014; Blythe & Joseph, 2011; Reichle et al., 2013), make shorter saccades (Blythe et al., 2006), are more likely refixate words before leaving them (Joseph, Liversedge, Blythe, White, & Rayner, 2009), and they appear to extract information from a narrower window of the text around fixation (Rayner, 1986). These differences are observed despite children being as efficient as adults at

extracting visual information from the text (Blythe, Liversedge, Joseph, White, & Rayner, 2009; Blythe, Häikiö, Bertram, Liversedge, & Hyönä, 2009). It seems unlikely that the difference between adults' and children's eye movements are the result of motor control factors or differences in encoding strategies. Instead, it is likely that they reflect differences in skill and fluency in text processing.

To further elucidate these age-related differences, Reichle et al. (2013) simulated adults' and children's eye movement data with the E-Z Reader model (reviewed in section 1.3.1.; Reichle, 2011; Reichle, Pollatsek, Fisher, & Rayner, 1998). These simulations enabled several predictions regarding how changes in oculomotor, visual, and linguistic processes influence the trajectory of reading development. Several simulations led to the conclusion that the differences between adults and children reflect differences in lexical processing rates as opposed to differences in oculomotor control.

In addition to these developmental differences in eye movements during reading between children and adults, skilled adult readers do not read in the same way. Research has shown that the eye movement patterns of highly skilled readers are quantitatively different to those of less skilled readers (Ashby et al., 2005; Bélanger, Slattery, Mayberry, & Rayner, 2012; Kuperman & Van Dyke, 2011; Rayner, Slattery, & Bélanger, 2010; Slattery & Yates, 2018; Veldre & Andrews, 2014, 2015a, 2015b). Fixation durations have been noted to differ between skilled adult readers, with poorer readers making more frequent, longer fixations and relying more on phonological activation than better readers (Jared, Levy, & Rayner, 1999). Poorer readers also rely more on context to support word processing (Ashby et al., 2005), have smaller perceptual spans (Veldre & Andrews, 2014), and extract less information from words in their parafovea than do better readers (Veldre & Andrews, 2015a, 2015b). This line of evidence converges with the developmental work and suggests that the eye movements of readers reflect reading skill.

1.3.4. The return-sweep in reading

Return-sweeps are saccadic eye movements that position the fovea as to fixate new information at the start of a line. Between the 1960s and 1990s, research concerned with the basic characteristics of return-sweeps and the influence of typographical factors on their accuracy was undertaken. In recent years the study of return-sweeps has been minimal. This is surprising considering Suppes's (1994)

assertion that comprehensive models of eye movement control during reading would have to take into consideration not only progressive and regressive saccades, but also return-sweeps and the corrective saccades that frequently follow these eye movements.

1.3.4.1. Return-sweep saccades

Return-sweep saccades are a special case of a large goal-directed saccade during reading. In most experiments, large saccades occur as a result of instruction (e.g. saccade between two distinct stimuli in the visual field). However, return-sweeps are natural saccades that are driven by demands of text processing. Return-sweeps are typically launched close to the end of the line and take 30-125 ms to complete. The fixation following a return-sweep is generally 5- to 7-characters from the leftmost letter on a line. Based on the data of Heller and Radach (1992) it is generally assumed that readers will target a position on a new line where word identification processes are optimal. In their study, 4 participants read a classic novel containing 48,000 words. While the authors estimated that the initial fixation would land on characters 3 and 4, the actual landing position was slightly shifted to the right. They argued that this dissociation was similar to the preferred and optimal viewing locations typically observed in studies of isolated word recognition and single sentence reading (see Rayner, 1998 for discussion). However, subsequent data presented by Radach and Heller (1993) showed return-sweep landing position is independent of the length of the first word on a new line. It is therefore assumed that readers tend to target a similar location regardless of word length as this strategy, on average, is most likely to promote efficient word identification and lexical processing.

Because return-sweeps move the eyes a greater distance than other reading saccades, it is expected that they will be influenced more by these error components. However, return-sweeps very infrequently overshoot their target (Hofmeister et al., 1999). Instead, return-sweeps tend to land approximately 7-9 characters from the start of the line (Rayner, 1998), with a substantial portion of return-sweeps being followed by an immediate leftward saccade that brings the eye towards the left margin (Hofmeister, Heller, & Radach, 1999). This indicates that return-sweeps have a systematic tendency to undershoot the start of the line. This tendency to undershoot the target is similar to the pattern of error observed in non-reading tasks

where saccades of similar lengths tend to be hypometric—they fall slightly short of their intended target (Gilchrist, 2011). However, it is important to differentiate between these tasks as the goal of a return-sweep is driven by text processing while saccades in non-reading tasks are driven by instruction.

Early investigations into return-sweeps were motivated by applied questions. Tinker and colleagues were concerned with the influence of line length on the readability of the text (Tinker, 1963). Across several studies, they found reading time increased with increasing line length (Paterson & Tinker, 1940). Increasing line length was associated with an increased occurrence of corrective saccades. Thus, these authors attributed the longer reading times associated with longer lines to a difficulty in returning to the start of a new line and the increased need for corrective saccades. While the length of the passages read by participants in Paterson and Tinker's study were identical (30 words each), it is important to note that the passages viewed by participants were not counterbalance across conditions. This makes it difficult to determine whether this effect varies directly as a function of line length or if it is modulated by the difficulty of the text in each condition. Furthermore, each condition differed in the amount of words that a reader could target as they move towards the start of a line. Subsequently, this could have influenced saccade targeting between conditions. Despite this limitation, subsequent studies have reported similar findings with reading speed and the frequency of return-sweep undershoot errors (RUE) being influenced by line length. In general, the frequency of RUEs increases with the length of the intended return-sweep, with shorter lines yielding fewer RUEs (Beymer, Russell, & Orton, 2005; Schneps et al., 2013).

While Tinker and colleagues' early work monitored how readers read from physical copies of the text, researchers in ergonomics have investigated the optimum line length for reading from computer screens. In contrast to print studies, some studies report that reading on computer screens favours longer lines (100 characters), or at least show no preference towards shorter lines (75 characters; Dutchnick & Kolers, 1983; Dyson & Kipling, 1998). Furthermore, these studies found no difference in comprehension when reading shorter and longer lines. To resolve the discrepancy in findings, it is noted that monitors are typically further from the reader than hard copy pages, so a shorter printed line width may subtend a similar visual angle on the eyes as a wider line width on a monitor (Gould, Alfaro, Finn, Haupt &

Minuto, 1987). Therefore, it may be proposed that shorter lines facilitate reading efficiency. This is reflected in the work of Beymer et al., (2005), who demonstrated that longer lines reduced the number of required return-sweeps, but increased regressions. Furthermore, it was found that a single saccade is needed to return from the end of one line to the start of another when line length was short. Heller (1982), who varied lines to be between 13° or 28° of visual angle, obtained similar results. For the shortest line, corrective saccades were required following 10% of return-sweeps. This was increased to 53% of return-sweeps for the longest lines.

Prior to this thesis, Hofmeister et al. (1999) reported the most comprehensive examination of return-sweep behaviour. In their study, 9 participants read 50 passages of text. Each text was formatted so that its horizontal extent was 10°, 16°, or 22° of visual angle (37-, 59-, and 81-characters respectively). They examined the influence of this manipulation on several return-sweep parameters: return-sweep launch position, return-sweep landing position, the frequency of corrective saccades, and the amplitude of corrections. Return-sweeps were generally launched relatively close to the end of the line (approximately 4 characters). However, there was a numerical trend for this distance to increase for longer lines. It is important to note, however, that Hofmeister et al. (1999) provided no statistical analysis of this effect, so it is important to approach this result with caution. Hofmeister et al. (1999) did provide statistical analysis for the remaining measures. They found that increasing line length was associated with a substantial rightward shift of landing positions with the frequency of corrective saccades and the amplitude of these corrective increasing similarly. Thirty-three percent of return-sweeps in the 10° condition were followed by a corrective saccade, and this increased to 50% in the 16° condition and 68% in the 22° condition. The authors also questioned whether corrective saccades were a product of retinal feedback following the return-sweep or a result of distance traversed by the saccade. To address this question, Hofmeister et al. (1999) examined the effect of line length on making a corrective saccade for identical landing positions. Their logic followed that if readers initiate more corrective saccades in the long compared to the short condition even for identical landing sites, the preceding saccade would have exerted some influence on the initiation of a correction. A comparison of means indicated that more corrections were made in the long line condition than the short or medium conditions. Therefore, the distance

traversed by the saccade does indeed influence the likelihood of making a corrective saccade.

In a second experiment, Hofmeister et al. (1999) aimed to investigate the nature of visuospatial information used to programme a return-sweep. In this study they examined two competing hypotheses. The first, termed the spatial map hypothesis, suggests that as readers pass through each line, they are building a representation of the text. This representation is subsequently used to make pre-programmed return-sweeps across the whole body of text. The second hypothesis suggests that readers program each return-sweep separately based on the information acquired during a line-final fixation. To examine these hypotheses, Hofmeister et al. (1999) had 9 participants read various passages of text in which the justification was altered. If the spatial map hypothesis of return-sweep planning were true, it would predict that when the text is right aligned saccadic error would increase as readers' representations would differ from the distance required of the saccade. However, the justification of the text had no influence on the execution or the accuracy of return-sweep saccades. Therefore, they concluded that each return-sweep is programmed separately at the end of each line.

Return-sweep accuracy is not only influenced by line length, it is also influenced by the difficulty of the task and reading skill. In the first of several studies, Heller (1982) examined the relationship between text difficulty and the prevalence of corrective saccades. Participants read text defined by raters as being easy, average, or difficult. While line length influenced the accuracy of return-sweeps (as indexed by fewer corrective saccades), the difficulty rating did not. Here it is important to note that there were very few observations of corrective saccades in the short line condition. This will have subsequently meant that the reliability of the statistical methods applied would have been reduced. When the number of fixations was taken as a measure of text difficulty, the frequency of corrective saccades appeared influenced by text difficulty. Thus, the effect of text difficulty could potentially influence return-sweep accuracy.

In a second experiment, Heller (1982) examined the influence of reading instruction on return-sweep accuracy. Here, participants were instructed to read text and identify spelling errors. The text consisted of 17 lines, and an error occurred on three of these. Return-sweep accuracy was compared for lines in which there was an error and those in which there was no error. On average, there were more corrective

saccades following an error than when there was no error yet this effect was not statistically significant. In an addition, compared to the task in which readers read for comprehension, significantly more corrective saccades were required when reading for spelling errors. This indicates that return-sweep accuracy can be modulated by reading instruction.

A rather more interesting pattern of results presented by Heller (1982) is that those who performed poorly on a word identification task were more likely to require additional corrective saccades following a return-sweep. Additionally, differences have been observed in return-sweep accuracy between adults and children. For instance, Netchine, Guihou, Greenbaum, and Englander (1983) that children's return-sweeps were more likely than adults' to undershoot their target—requiring more frequent corrective saccades. Furthermore, dyslexic readers required more corrective saccades when reading aloud compared to typically developing readers (Trauzettle-Klosinski et al., 2010). Together these results show that reading ability influences, at the very least, the accuracy of return-sweep saccades.

From this section it is clear that reader's return-sweeps are often inaccurate and frequently require a corrective saccade towards the left margin. Typographical influences on return-sweep accuracy demonstrates that the distance traversed by the saccade strongly influences the likelihood of requiring a corrective saccade. However, the accuracy of return-sweeps could also be driven by global effects (Findlay, 1982). By this account, readers may intend on targeting a specific word, but the crowding of the words on a new line may result in saccadic undershoot. An error signal following the return-sweep would then be likely to influence the execution of a corrective saccade towards the original target. Given that return-sweeps can either be accurate (cases which require no corrective saccade) or inaccurate (case which require a corrective saccade) it indicates that there are two distinct populations of fixations that follow a return-sweep. The focus of this section was on the saccade itself. The following section will explore differences between the populations of fixation preceding and following a return-sweep and consider the role that these fixations play in lexical processing.

1.3.4.2. Return-sweeps and fixation durations

For the purpose of examining the effects of return-sweep execution on lexical processing, this thesis defines four specific populations of reading fixations (intra-

line, line-final, accurate line-initial, and undersweep). Intra-line fixations are those non-adjacent to return-sweeps. Fixations that immediately precede a return-sweep are referred to as line-final fixations. Line-initial fixations are those that follow a return-sweep and can be categorised into accurate line-initial and undersweep fixations. Accurate line-initial fixations are those that land close enough to target of the return-sweep so that readers can begin their rightwards pass through a given line of text. Undersweep-fixations are line-initial fixations that are immediately followed by a corrective saccade towards the left margin. That is, undersweep-fixations reflect cases in which the return-sweep fell short of its intended location and required a corrective saccade prior to the rightwards pass.

As readers progress towards the end of a line, fixation durations decrease (Kuperman, Dambacher, Nuthmann, & Kliegl, 2010). Accordingly, line-final fixations are shorter than intra-line fixations (Abrams & Zuber, 1972; Hawley, Stern, & Chen, 1974; Rayner, 1977). It is argued that this reduction in fixation duration for line-final fixations reflects a reduced need for parafoveal processing at the end of a line (Rayner, 1977). However, Kuperman, Dambacher, Nuthmann and Kliegl (2010) and Mitchell, Shen, Green, and Hodgson (2008) suggested that oculomotor programming may be responsible for these end-of-line effects. Similarly, Abrams and Zuber (1972) argued that shorter line-final fixations are the result of return-sweep planning. Consistent with this planning account, Hofmeister (1997) reported that text degradation of 50% led to a 20 ms increase in duration for all fixations except line-final fixations. At the very least, this indicates that line-final fixations are less influenced by stimulus quality.

Recall that line-initial fixations can be classified as either accurate line-initial or undersweep-fixations. Accurate line-initial fixations are those that reach their intended location without requiring a corrective saccade. This population of fixations tend to be 30-50 ms longer than intra-line reading fixations (Rayner, 1977; see also Abrams & Zuber, 1972; Dearborn, 1906; Hawley et al., 1974). Stern (1978) proposed that binocular coordination processes may be responsible for longer line-initial fixation durations. That is, a longer period of reorientation is required to resolve the increased magnitude of fixation disparity that follows return-sweeps while the first unit of information on a line is processed. Yet Stern's explanation is difficult to discern from a novel account introduced throughout this thesis which attributes the increased fixation duration following accurate return-sweeps to a lack

of parafoveal pre-processing for information on a new line. In two experiments, Pollatsek, Raney, Lagasse, and Rayner (1993) reported that readers do not generally obtain preview of the line below fixation. In their first experiment, participants read passages of text while the availability below the line was manipulated using a variant of the moving window paradigm. Reading was no slower when letters were masked below the line. However, when a series of dissimilar letters replaced the words on the second line, a 6% reduction in reading rate was noted, though this was not the case for strings of Xs, visually similar letter, or text change conditions. The authors argued that this difference in the dissimilar condition was inhibitory rather facilitative. In the second experiment, readers were asked to scan the text for words while the lines below fixation was masked to a varying degree. While participants occasionally detected targets below fixation, the rate of detection when the target was placed below fixation was very small (less than 10%). It therefore appears that in reading, little visual information is extracted below the currently fixated line. Based on this evidence it would appear that all processing at the start of the line takes place foveally.

Undersweep-fixations refer to the population of fixations that intervene return-sweeps and corrective saccades (e.g. Hofmeister et al., 1999). Undersweep-fixations tend to be shorter than intra-line reading fixations (i.e. 130 ms; Heller, 1982). Given that undersweep-fixations are typically shorter than the point at which lexical variables influence the duration of a fixation (see Reingold & Sheridan, 2018 for a discussion), it is widely assumed that these brief fixations are uninvolved in linguistic processing (Hawley et al., 1974; Shebilske, 1975). Instead they are generally considered as an oculomotor response to retinal feedback when readers reach the start of a line which represents the deviation of a return-sweep landing position from its intended goal (Becker, 1976; Hofmeister et al., 1999). Undersweep-fixations are remarkably similar to express saccades during non-reading tasks. Express saccades are typically 80 to 130 ms in duration and are considered the result of advanced preparation of an oculomotor program towards a target (Fischer & Boch, 1983; Fischer & Weber, 1993; Heeman, Van der Stigchel, 2017; Marino, Levy, & Munoz, 2015). Prior to this thesis, undersweep-fixations have been considered as a nuisance. However, as will become clear, they have important implications for the processing of information at the start of the line.

1.4. Computational Models of Eye-Movement Control during Reading

Sophisticated models of eye movement control have led to the development of specific and testable hypotheses about eye movement control during reading (see Rayner, 2009b). Yet, as currently implemented, these models make no specific predictions about reading at line boundaries. This results from the tendency to fit models to data from single sentence reading studies, which are devoid of return-sweeps. Throughout this thesis, the assumptions of these models will be considered to determine the extent to which established parameters can explain lexical and non-lexical effects at line boundaries.

While numerous models of eye movement control during reading exist (see Engbert & Kliegl, 2011 and Reichle, 2011 for discussions), two models currently dominate the field: E-Z Reader (Reichle, Pollatsek, Fisher, & Rayner, 1998; Reichle, Rayner, & Pollatsek, 2003; Pollatsek, Reichle, & Rayner, 2006; Reichle, Warren, & McConnel, 2009), and SWIFT (Engbert, Longtin, & Kliegl, 2002; Engbert, Nuthmann, Richter, & Kliegl, 2005; Schad & Engbert, 2012). While there are several similarities between these models, the main point of dispute between them is the number of words that can be processed at the same time and the order in which words can be processed. As will become clear, E-Z Reader assumes serial lexical processing where the processing for an upcoming word ($n+1$) is dependent upon lexical processing for word n being complete. SWIFT, on the other hand, assumes that lexical processing occurs in parallel, such that all words within the perceptual span are all lexically processed at the same time. This will of course have implications for the processing of information following a return-sweep, particularly when readers land short of the line-initial word. The purpose of this section is only to provide readers with an overview of the architecture of E-Z Reader and SWIFT and to hypothesise on how these models may be extended to account for return-sweeps as parsimoniously as possible given their current implementation. It should be made clear that these models do not and cannot account for return-sweep saccades as they currently implemented.

1.3.1. The E-Z Reader Model

Two major assumptions lie at the core of E-Z Reader. The first is that attention is allocated across the text in a strictly serial manner to one word at a time. The second is that lexical processing drives the eyes through the text. E-Z Reader

posits that lexical processing occurs in two stages. The first stage (L1) is the familiarity check which involves an assessment of how familiar a word's orthographic form is. The duration of L1 is influenced by the fixated word's frequency and predictability given its prior context. The duration of L1 is shorter for high-frequency words and words that are predictable. Upon the completion of L1, a saccade program will be initiated. Thus, when readers fixate a high-frequency word, the preparation of a saccade away will occur earlier than it does for a low-frequency word.

The second stage (L2) is lexical access during which a word's meaning become activated. L2 is modulated by a word's frequency and predictability and is proportional to L1. Upon completion of L2, attention is shifted to the next word in parafoveal vision and L1 begins for word $n+1$. During the completion of L2, a saccade to the parafoveal word is programmed. The time taken to program a saccade is fixed within E-Z Reader. Consequently, a word can be fully identified in parafoveal vision prior to it being fixated. This decoupling between attention and saccade execution can explain why preview benefits for information from word $n+1$ are observed during reading (see Schotter et al., 2012). This decouple is also capable of explaining foveal load effects. When word n word is low-frequency, L2 takes longer to complete resulting in diminished processing for word $n+1$ prior to a saccade (e.g. Henderson & Ferreira, 1990).

It is well established that short words will often be skipped, as will predictable and, to an extent, highly frequent words. Within EZ, the skipping of words is explained by its assumptions about the time course and independence of lexical processing and saccade planning. E-Z posits that saccades are programmed in two stages. The first stage lasts approximately 125 ms and is referred to as the labile stage. Within this stage saccade programmes can be cancelled and replaced. In the second non-labile stage, which lasts approximately 25 ms, saccades cannot be cancelled. If the familiarity check (L1) for word $n+1$ completes during the first stage of saccade planning, the saccade to $n+1$ will be cancelled and a programme to $n+2$ will be initiated. This will result in a skip for word $n+1$. This sequence of events will be more probably for shorter words as their orthographic components can be more easily completed in parafoveal vision, allowing the L1 to be completed more efficiently. As L1 is typically shorter for highly predictable and high-frequency

words, the probability of L1 completing prior to the first stage of saccadic programming finishing is also increased for these words.

E-Z Reader assumes that saccades are targeted towards word centres. As a result, the length of an intended saccade will be equal to the distance between the current fixation location and the centre of the targeted word. Within E-Z Reader, range error (McConkie et al., 1988) is programmed so that for every character that the intended saccade is greater or less than 7-characters, there will be 0.4-characters of over- or undershoot. E-Z Reader additionally encompasses a parameter for random motor error. The random error component results in additional error in landing position that is either to the right or left of word centres and increases proportional to saccade length. The implementation of these error sources has led to E-Z successfully simulating landing positions within words (Reichle, Rayner, & Pollatsek, 1999).

As currently implemented, E-Z Reader makes no predictions about return-sweep behaviour. However, within the context of E-Z Reader, a return-sweep may be viewed as any other inter-word saccade with the exception that the shift of attention to the first word of the next line does not result in the start of parafoveal pre-processing of the next word (the first word of the next line), due to this word being located in the periphery. Instead, lexical processing of line-initial words must wait for these words to be both attended and located in the fovea or parafovea (i.e. after execution of the return-sweep). Such a model would predict that fixation times would be longer on accurately fixated line-initial words following a return-sweep compared to words fixated during the normal left to right (for English) reading pass within a line. It would also predict that the effects of word frequency and predictability would remain the same as for other words.

1.3.2. The SWIFT Model

Contrary to E-Z Reader, the (Autonomous) Saccade-generation with Inhibition by Foveal Targets (SWIFT) model assumes that attention is distributed as a gradient across all words in the perceptual span. In its most recent revision (SWIFT 3; Schad & Engbert, 2012), the spatial extent of the perceptual span is modulated by the processing difficulty of the fixated word. When processing demands are high, it assumes that the perceptual span is reduced. However, the span will typically contain words $n-1$, n and $n+1$, with the occasional inclusion of words $n+2$ (Kliegl,

Nuthmann, & Engbert, 2006). While all words within the perceptual span can be processed in parallel, attentional resources are allocated in a graded manner. Words in central vision receive more attentional resources than those further from fixation. SWIFT assumes that the processing of multiple words occurs via independent channels, such that the processing of one word does not influence the processing of another.

Within SWIFT, saccades are generated based on a random timer with the generation of saccades occurring when the random timer reaches zero. The rate at which the timer reaches zero is not fixed. Instead the timer is inhibited by the processing difficulty of the fixated word. As a result, low-frequency words typically lengthen the time taken for the random timer to reach zero leading to longer fixations on low-frequency words. Saccades are targeted based on an activation field in which words in the perceptual span compete for selection. Words that have the most activation when the random timer reaches zero will become the saccade target. Activation for a word is determined by its current processing status with lexical processing occurring in two stages. A pre-processing phase in which word activation builds from zero to a maximum L_n , and a lexical completion phase where it returns back to zero. Maximum activation (L_n) for a word is a function of word difficulty as estimated by word frequency. Within SWIFT, word predictability does not influence processing difficulty but rather lexical processing rate. Furthermore, predictability influences rates differently in the two phases of lexical processing. Within SWIFT, the target of the saccade is determined by a word's activation. When fixating word n it is possible that word $n+2$ may have greater activation than word $n+1$. In such cases readers will make a saccade towards $n+2$ and skip word $n+1$. Furthermore, during pre-processing, predictability decreases the lexical processing rate so that more predictable words maintain a lower activation and are thus more likely to be skipped.

Similar to E-Z Reader, SWIFT assumes that saccades are susceptible to both systematic and random error. Again, SWIFT assumes that saccades are targeted towards the centre of an upcoming word and the length of a saccade is equal to the distance between the current fixation location and the centre of the targeted word. Within SWIFT, range error (McConkie et al., 1988) is programmed so that for every character that the intended saccade is greater or less than 5.4-characters, there will be 0.41-characters of under- or overshoot, respectively.

A complication of applying the principles of SWIFT to the study of return-sweeps is that the model requires words to have activation in order for them to be selected as targets of saccades. However, these words need to be in the attentional window for activation to build and the first word of a new line falls well outside of this window during normal reading. Therefore, either the core model assumptions would need to be altered or a new specific assumption for implementing return-sweeps would need to be added (such as assuming a return-sweep is planned once all the words on a current line have been processed). Assuming this issue was overcome without drastic changes to the rest of the model assumptions, then we could expect the following:

1. The duration of the line-initial fixation should be no longer than other reading fixations as it would derive from the same random timer processes.
2. Activations for the words on the new line would build from zero after the return-sweep once the words are within the window of attention resulting in increased refixations for words at the start of a line.
3. The effect of frequency on these activations and target selection would remain the same after a return-sweep as before it because it only influences the maximum activation and does not influence the change in activations over time. Moreover, the effect of frequency on fixation durations would remain the same.
4. The effect of predictability on the rate of change in activations would remain the same. However, given that word activations on the new line would start at zero, it would take time before they built up enough for predictability to influence target selection processes. This may lead to decreased skips and increased refixations immediately after a return-sweep.

1.5. Summary and theoretical scope

From the research discussed in this chapter, it should be evident that a great deal has been learned about saccadic eye movements during reading and non-reading tasks. With regards to reading, we know a great deal about the information that is utilised to determine the decision of when and where to move the eyes. Based on these findings, sophisticated computational models of eye movement control during reading—such as E-Z Reader and SWIFT—are able to model the pattern of saccades and fixations made by readers with a high degree of accuracy. Yet these models are

far from comprehensive. According to Suppes (1994), a truly comprehensive model of eye movement control during reading would have to account for return-sweep saccades and fixations at line boundaries if these models are able to accurately represent natural passage reading. It is hoped that the work presented throughout this thesis will provide several benchmark findings for the development of computational models that simulate reading at line boundaries. Before proceeding to the first empirical chapter, the lines of interest for each chapter are specified.

Chapter 2 is largely concerned with replicating previous findings in relation to line length and return-sweeps. During both non-reading and reading tasks it has been reported that the length of the saccade has been associated with increased undershoot error. The return-sweep is no different. When line length is used as a proxy for saccade length, landing sites are shifted to the right and undersweep-fixations are more common. It is these findings that we sought to replicate. In addition, several studies have reported distinctions between the durations of fixations adjacent to return-sweeps and those that occur intra-line. Yet no single study has jointly examined the duration of all four fixation populations (intra-line, line-final, accurate, undersweep) in a single analysis. The specific questions in relation to return-sweep parameters are as follows: at which point do readers execute a return-sweep, where do they land relative to the start of the line, and what is the frequency of errors following a return-sweep?

In chapter 3, the influence of return-sweep execution on binocular coordination is considered. For brevity's sake, binocular coordination processes were not reviewed in the current chapter. Therefore, if a reader finds the literature reviewed in chapter 3 to be insufficient for an understanding of the material, they are referred to Kirkby, Webster, Blythe, and Liversedge's (2008) review of binocular coordination during reading and non-reading tasks. Chapter 3 largely describes the characteristics of binocular coordination across multiline texts. This is of theoretical importance as it enables a direct examination of Stern's (1978) argument that line-initial fixations are longer because of a need to resolve greater disparity following return-sweeps.

After examining the oculomotor aspects return-sweeps, chapter 4 begins to question how lexical processing at line boundaries is influenced by return-sweeps. This chapter consists of two experiments and a corpus analysis. In Experiment 1, we examined whether predictability effects could be observed for the first word on a

new line. As will become clear in chapter 4, predictability effects are reported as absent under conditions where readers are unable to acquire valid preview prior to direct fixation. In the case of return-sweeps, predictability effects should not be observed as it is unlikely that readers are able to obtain preview of the line-initial word. In a second experiment the joint effects of lexical frequency and predictability are examined for line-initial words in attempt to inform modelling. This experiment also examines how undersweep-fixations contribute to the processing of line-initial words. This chapter closes with a consideration of what the findings mean for the E-Z Reader model.

In chapter 5, the focus moves towards the role of undersweep-fixations during reading. In chapter 4, Experiment 2, it is reported that undersweep-fixations provide readers with some preview of the first word on the line. This chapter further considers the role that undersweep-fixations play during a subsequent pass on a line. While exploratory in nature, this chapter provides some of the strongest evidence to suggest that return-sweep error is not uninvolved in linguistic processing as a review of the literature may suggest. The implications of the data are discussed in reference to data analysis and models of eye movement control.

While chapters 2 through 5 are concerned with return-sweeps in skilled adult readers, chapter 6 is concerned with return-sweeps and reading development. This chapter includes two separate lines of investigation. The first compares return-sweep and corrective saccade parameters between adults and children as they read identical multiline texts. The second investigates the effect of undersweep-fixations on a reader's subsequent pass through the line. Specifically, it investigates whether, similar to adults, children are able to process linguistic information during an undersweep-fixation. This thesis then ends with a discussion of these findings in relation to linguistic processing across line breaks, computational models of eye movement control during reading and considered future directions for the study of return-sweeps.

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Chapter Two

The Basic Characteristics of Return-sweep Saccades

Portions of the following chapter has been submitted for publication as Parker, A. J., & Slattery, T. J., (2017). Return-sweep saccades and individual differences amongst skilled adult readers. *Scientific Studies of Reading*.

2.1. The current study

Research on return-sweeps has primarily focused on applied aspects such as the influence of typographical factors on return-sweep accuracy. This opening enquiry aimed to replicate the finding that longer lines are associated with a shift in landing positions to the right of the left margin and an increased frequency of corrective saccades. In addition to these replications, the duration of fixations adjacent to return-sweeps were examined. Previous investigations of fixation durations adjacent to return-sweeps have typically reported means without statistical analysis (e.g. Rayner, 1977). Therefore, the durations of “return-sweep fixations” are examined relative to intra-line reading fixations. Rather than reintroduce the literature discussed in chapter 1, the specific predictions addressed in this chapter are outlined with reference to the reviewed material below.

Line-final fixations, those just prior to a return-sweep, represent the launch site of the return-sweep. Line-final fixations typically occur 5- to 7-characters from the end of the line (Rayner, 1998). Investigations of line length have typically failed to report how the location of line-final fixations is influenced by this typographical manipulation. Hofmeister, Heller, and Radach (1999) reported that line-final fixations occur further from the end of the line with increasing line length. However, no statistical consideration of such an effect was reported. For lines of 37-characters, line-final fixations occurred, on average, 3.9 characters from the end of the line. For lines of 59- and 81-characters, line-final fixations occurred 4.2- and 4.7-characters away from the end of the line respectively. Based on these numerical trends, it is expected that line-final fixations would occur further from the end of a line when line length is long. Such a finding would be theoretically interesting as it may suggest that readers avoid fixating extreme locations to reduce the distance of the required return-sweep.

Line-initial fixations, those that immediately follow a return-sweep, represent the landing position of the return-sweep. Line-initial fixations typically occur 5- to 7-characters from the start of the line and vary as a function of line length. Hofmeister et al. (1999) reported that return-sweep landing positions were 6.0-, 7.8-, and 10.1-characters from the start of the line for lines of 37-, 59-, and 81-characters. Recall from Section 1.3.4. of this thesis, return-sweeps have two trajectories. Return-sweeps either reach their target or require a corrective saccade to position the eyes closer to their target. As a result of these trajectories it is informative to examine return-sweep landing position separately for these two distinct groups of line-initial fixations. Given that accurate line-initial fixations are likely to be those that land close to the start of the line and promote efficient processing of information at the saccade target location, it is predicted that the landing position of accurate line-initial fixations would not vary as a function of line length. Therefore, any difference between conditions in landing position would result from undersweep-fixations landing further from the start of the line for longer lines. Such a finding would indicate that saccadic error is responsible for these line length effects rather than line length itself systematically influencing landing positions.

Several studies have reported that longer lines are associated with an increased rate of corrective saccades following a return-sweep (Beymer, Russell, & Orton, 2005; Dutchnicky & Kolars, 1983; Dyson & Kipling, 1998; Heller, 1982; Paterson & Tinker, 1940; Schneps et al., 2013; Tinker 1963). Consistent with these observations, when target eccentricity is further away from the current fixation in non-reading tasks, there is an increased prevalence of corrective saccades (c.f. Ohl, Brandt, & Kliegl, 2011). Therefore, it is predicted that longer lines would be associated with an increased frequency of corrective saccades. This prediction assumes that saccade length determines the frequency of corrective saccades. An alternate account suggests that corrective saccades are not a product of saccade length but rather a response to a deviation of return-sweep landing position from the saccade's target which, if exceeding a tolerance threshold, triggers a corrective saccade (Becker, 1972). Such an account would predict that as the landing position of return-sweeps shifts to the right (or further from the start of the line), there would be an increase in the requirement of a corrective saccade. Of course, these two accounts need not be mutually exclusive. Instead, both could codetermine the occurrence of a corrective saccades following a return-sweep.

Hofmeister et al. (1999) reported that, following a corrective saccade, readers' fixations were closer to the left margin than if a return-sweep had been accurate. Based on this finding, a similar effect is predicted in the current experiment. In relation to the influence of line length on reader's line-initial viewing position, Hofmeister et al. (1999) reported no statistical analysis. A comparison of means indicated similar landing positions following a correction, while accurate line-initial fixations were shifted to the right for longer lines. Therefore, the current experiment aimed to provide a statistical analysis of line-initial viewing locations. It is predicted that the viewing location would be shifted to the right following a corrective saccade. An effect of line length was not predicted here as it was expected that line-initial viewing locations would be similar between line length conditions in order to afford efficient word processing in these locations.

The predictions outlined previously are concerned with return-sweep and corrective saccade parameters. Below predictions are outlined for the pattern of fixations preceding and following a return-sweep. As noted in Section 1.3.4.2., line-final and undersweep-fixations are shorter than intra-line reading fixations while accurate line-initial fixations are longer. An identical pattern of results is predicted here. In relation to line length, an influence of line length is not predicted on any fixation population other than undersweep-fixations. Corrective saccades of greater amplitudes are typically associated with a reduced duration (Becker, 1972; Kapoula & Robinson, 1986; Prablanc & Jeannerod, 1975). Becker (1972) suggested that when an image of a target falls on the retina within an area in which visual acuity is still high, a correction is not urgent. However, when the image falls far from the location that requires processing a saccade will be executed more rapidly. Thus, an effect of line length may result from the landing position of the return-sweep rather than the saccade length itself. It is of course important here to note the findings of Ohl et al. (2011) who reported an effect of both saccade length (indexed by target eccentricity) and initial saccade error. Therefore, it is predicted that undersweep-fixations will be shorter when line length was longer and the line-initial fixation landed further from the left margin.

2.2. Method

To examine the predictions outlined in Section 2.1., the eye movements of participants were recorded while they engaged in the reading of multiline texts. In

order to replicate previous findings in relation to line length, lines were formatted to one of two lengths. These lengths exceeded those in previously published work (both in terms of visual angle and character spaces) to ensure that a substantial number of undersweep-fixations occurred.

2.2.1. Participants

Fifty-two native English speakers from the Bournemouth University community participated in the study. All had normal or corrected-to-normal vision, were native English speakers, and indicated that they had no history of reading impairment. Four participants were excluded due to track loss. This left 48 participants, with a mean age of 26.48 years ($SD= 14.83$), who were naïve to the purpose of the experiment.

2.2.2. Apparatus

Eye movements were recorded via an SR Research EyeLink 1000 eye-tracker sampling once per millisecond. Although reading was binocular, monocular data was recorded from the right eye for all but four participants¹. Text was presented in black letters on a white background using a non-proportional font (Consolas) on a BenQ XL2410T LCD monitor with a 1920 x 1080 resolution. Participants were seated 80 cm from the monitor so that 3.57 letters equated to 1° of visual angle. A forehead rest was used to minimise head movements and a VPixx five button response box was used to record responses.

2.2.3. Materials

Experimental stimuli consisted of 20 passages of text. Each passage contained three-to-six sentences displayed across three-to-five lines (see Figure 2.1), which were formatted to one of two line lengths: 75 characters (21° of visual angle) or 115 characters (32° of visual angle). Words in the text varied in length from 1 to 12 letters (mean= 4.35) and had an average Zipf frequency (Van Hauen, Mandera, Keuleers, & Brysbaert, 2014) based on the SUBTLEX database (Brybaert & New, 2009) of 5.80 (range: 1.30 to 7.67). Passages were counterbalanced so that each participant read an equal number in each condition and over all participants each passage was seen an equal number of times in each condition.

¹ Participant's left eye was tracked only if there was a problem calibrating their right eye due to issues such as glare from glasses.

As Henry whittled the stick for roasting marshmallows his father put
another log on the campfire. Later that night, raccoons got into their
food and made a mess of the campsite. His mother spent the whole of
the following day clearing up the camp.

As Henry whittled the stick for roasting marshmallows his father put another log on the campfire. Later that
night, raccoons got into their food and made a mess of the campsite. His mother spent the whole of the
following day clearing up the camp.

Figure 2.1. Example stimuli, where stimuli are formatted to one-of-two line lengths (75 or 115 characters).

2.2.4. Procedure

Participants provided informed consent and were familiarised with the equipment. They then completed a 9-point calibration and validation procedure. Errors above 0.4° of visual angle were repeated. Prior to viewing stimuli, a black 2° x 2° square, which coincided with the left side of the first letter in the stimulus, appeared on the screen. Once a stable fixation was detected in this area, the stimulus was presented. Presentation order was randomised and participants were instructed to read silently for comprehension. Comprehension questions appeared after a third of items. These ‘yes/no’ questions required participants to respond by pressing one of two buttons on the response box.

As part of a wider experiment, the 20 experimental items were embedded in a larger list of stimuli containing four practice paragraphs and 40 fillers. Following the eye-tracking task, participants completed individual differences tests in the following order: reading comprehension, spelling dictation, and misspelled word recognition. Upon completion, participants received payment of £10 or course credit as compensation for an hour’s participation.

2.3. Results

Across all participants 92% of comprehension questions were answered correctly. Fixations shorter than 80 ms, which were within 1 character of a previous or subsequent fixation, were combined with that fixation. All other fixations less than 80 ms or greater than 800 ms were excluded. Trials in which there were five or more blinks during passage reading were also removed. Analysis was conducted on the remaining 95.6% of the data (39,708) fixations.

For all analyses, eye movement data were analysed using linear mixed effects (LME) models in the R computing environment (R Development Core Team, 2012) using the lme4 package (version 1.1-17; Bates et al., 2018). The lmerTest package was used to compute p -values (Kuznetsova, Brockhoff, & Christensen, 2017). Regression coefficients (b), which estimate the effect size relative to the intercept, are reported as well as standard errors (SE), and t -values. Given the number of participants and observations per participant, the t -distribution will approximate the z -distribution; therefore, statistically significant cases are those where $|t| > 1.96$ (Baayen, Davidson, & Bates, 2008). Binary dependent variables, such as undersweep-fixation likelihood, were analysed using generalised linear mixed models (glmer function from package lme4) and the Wald z and its associated p -value are reported.

For all models, a full random structure for subjects and items, with random intercepts and slopes was initially adopted (Barr, Levy, Scheepers, & Tily, 2013). If models failed to converge, simplified random effects structures were fit to reduce overfitting of the random effects structure (Bates, Kliegl, Vasishth, & Baayen, 2015). In the simplified model, random effects parameters that were perfectly or near-perfectly correlated with others (suggesting overfitting) were removed, so long as these removals did not reduce model fit.

2.3.1. Return-sweep and corrective saccade parameters

Initially, three saccade parameters were examined: return-sweep launch site (the number of characters from the end of the line at which the return-sweep is launched), return-sweep landing position (the number of characters from the left margin of the new line), and the frequency of corrective saccades (the percentage of return-sweeps that required a corrective saccade). These metrics were examined for 2,764 line-final fixations (1,729 short line length condition) and 2,380 line-initial fixations (1,450 short line length condition). Return-sweep and corrective saccade parameters are shown in Table 2.1.

Table 2.1. Descriptive statistics for return-sweep and corrective saccade parameters as a function of line length.

Line Length	Return-sweep launch site	Return-sweep landing site	Frequency of undersweep-fixations (%)
Short	4.9 (2.95)	5.8 (3.00)	57.0 (49.53)
Long	5.3 (2.97)	8.4 (3.85)	76.5 (42.44)

Note. Return-sweep launch sites are shown as the characters from the end of a line. Landing site is given in characters from the start of a line. Means are displayed with standard deviations in parenthesis.

First, an LME model was fit to return-sweep launch site data. The distribution of return-sweep launch sites is shown in Figure 2.2. Prior to analysis, to exclude the extended right tail of the distribution, launch sites over 15 characters from the end of the line were excluded (6.33% of fixations). The model included a categorical fixed effect which coded line length condition ($lmer(dv \sim Line\ length + (1 + Line\ length | subject) + (1 + Line\ length | item))$). This analysis indicated that return-sweeps were launched at a similar distance from the end of the line regardless of the line length condition, $b = -.39$, $SE = .22$, $t = -1.76$, $p = .084$.

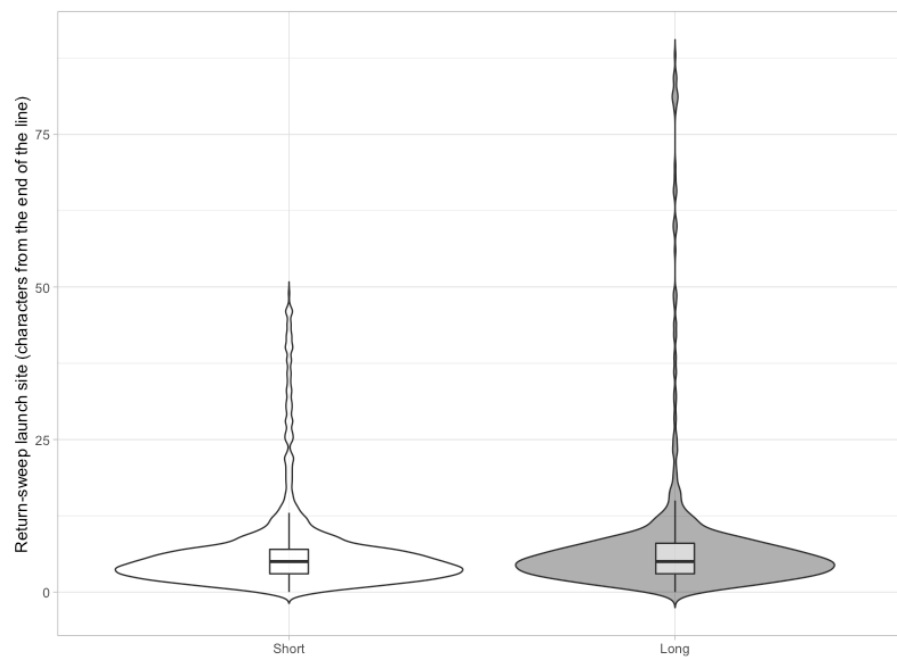


Figure 2.2. Violin plot for return-sweep launch position (characters from the end of the line) in each line length condition. Launch sites in the short condition are shown in white while launch sites in the long line condition are shown in grey. Boxplots show the first quartile, median, and third quartile.

To determine how line-initial landing position differed between conditions, an LME model was fit to landing site data. To account for the two distinct types of fixations that follow return-sweeps, an additional fixed effect coded whether the line-initial fixation was accurate or an undersweep-fixation² (the distribution of landing position is shown in Figure 2.3.). Prior to analysis, return-sweeps which landed more than 20 characters from the start of the line were excluded (2.8% of fixations). The final model included fixed effects for line length, fixation type (accurate or undersweep), and their interaction ($lmer(dv \sim Line\ length * Undersweep + (1 + Line\ length * Undersweep | subject) + (1 + Line\ length | item))$). Coding of the categorical variables meant that accurate line-initial fixations represented the intercept to which undersweep-fixations were compared. The fixed effect of line length did not influence landing position, $b = -.22$, $SE = .14$, $t = -1.64$, $p = .110$, indicating that accurate line-initial fixations landed in a similar position across line length conditions. Undersweep-fixations landed further from the left margin than did accurate line-initial fixations, $b = 3.61$, $SE = 0.16$, $t = 22.78$, $p < .001$. The interaction between line length and fixation type indicated that line length differences in landing site is larger for undersweep-fixations, $b = -1.00$, $SE = .13$, $t = -7.44$, $p < .001$.

² On occasion, return-sweep did overshoot the left margin. This occurred following 2.0% of return-sweeps. The majority of overshoots occurred in the short line condition (70.8%). Due to the infrequent occurrence of these saccades, overshoots were excluded from analysis.

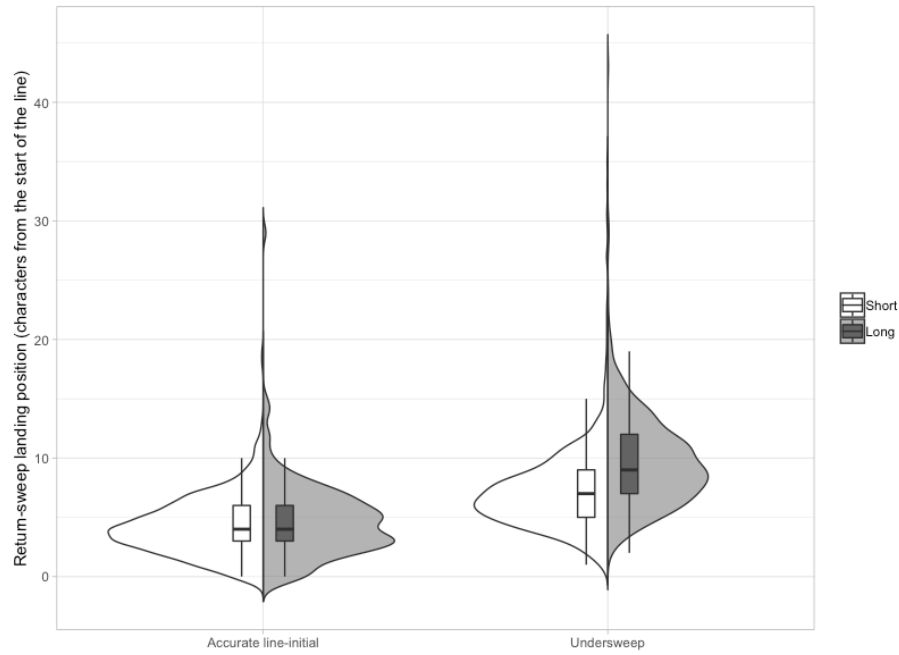


Figure 2.3. Split violin plot for return-sweep landing position (characters from the start of the line) in each line length condition for accurate line-initial and undersweep-fixations. The distribution of return-sweep landing position in the short line condition is shown in white while the distribution of return-sweep landing position in the long line condition is shown in grey. Boxplots show the first quartile, median, and third quartile per fixation population.

Next, a GLME model was fit to predict corrective saccade likelihood. The model included fixed effects for line length, landing position (distance from the start of the line), and their interaction ($glmer(dv \sim \text{Landing position} * \text{Line length} + (1 + \text{Landing position} | \text{subject}) + (1 + \text{Landing position} | \text{item}))$). Landing position was included as prior research has shown that the likelihood of making a corrective saccade increases as saccades fall further from their target (Ohl et al., 2011). Following our previous analysis, data for return-sweeps which landed more than 20 characters away from the left margin were excluded as these were very rare (.02%). Line length did not influence the likelihood of making a corrective saccade $b = -.11$, $SE = .08$, $z = -1.42$, $p = .157^3$. From Figure 2.4., line-initial fixations were increasingly

³ A reduced model, which included a fixed effect only for line length condition and the full random structure, indicated that a greater proportion of return-sweeps required corrective saccades in the long line condition, $b = -.57$, $SE = .09$, $z = -6.56$, $p < .001$. The inclusion of landing position in the GMLE model would suggest that landing position accounts for more variation in the data than line length.

followed by a corrective saccade the further away that they landed from the left margin, $b = .91$, $SE = .06$, $z = 14.07$, $p < .001$. The interaction between line length and landing position indicated that the effect of landing position did not differ between line length conditions, $b = -.06$, $SE = .03$, $z = 1.76$, $p = .079$.

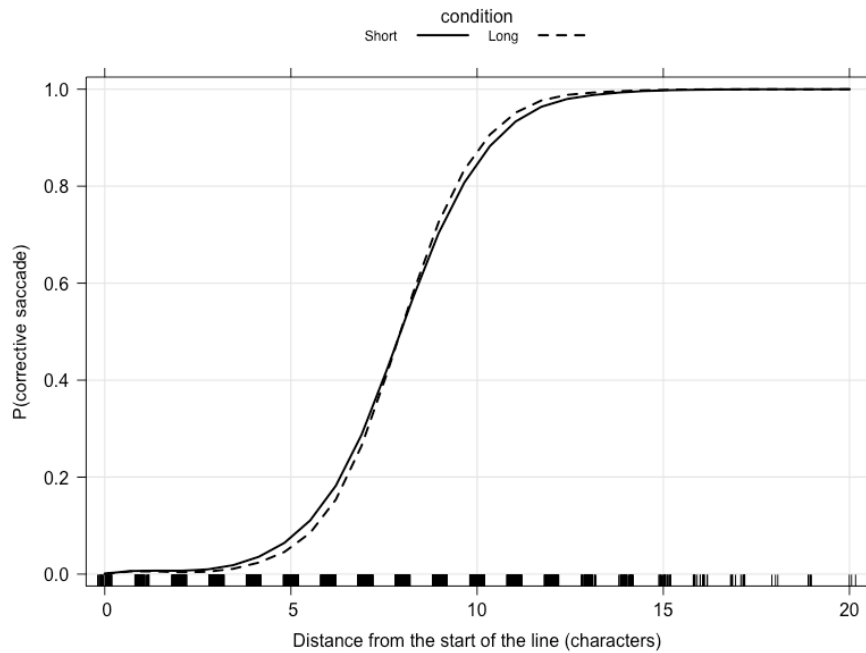


Figure 2.4. Probability of corrective saccade as a function of the distance from the start of the line (characters) and line length. The solid black lines represent model estimates for the short line condition and the dashed black line represents model estimates for the long line condition.

To examine whether corrective saccades brought reader's point of fixation closer to the left margin than did accurate line-initial fixations, landing positions following an accurate return-sweep were compared with landing positions following a corrective saccade. Referred to as line-initial viewing location, this metric represents the location from which the first saccade is made from left to right following a return-sweep. Prior to analysis, viewing locations greater than 10 characters away from the start of the line were removed as these cases were rare (1.2%; see Figure 2.5.). To examine whether viewing location statistically differed between line length conditions or between cases in which return-sweeps were accurate or followed by a corrective saccade, an LME model was fit to viewing location data. The model included fixed effects for condition, a categorical predictor

which coded whether the fixation occurred following an accurate return-sweep or a correction, and their interaction ($lmer(dv \sim Undersweep * Line\ length + (1 + Undersweep * Line\ length | subject) + (1 + Undersweep * Line\ length | item))$). Following an accurate return-sweep, viewing locations differ significantly between line length conditions, $b = -.21$, $SE = 0.11$, $t = -1.85$, $p = .080$. However, viewing locations were closer to the start of the line following a corrective saccade, $b = -1.12$, $SE = .13$, $t = -8.45$, $p < .001$. The interaction between line length and fixation type did not impact viewing locations, $b = .03$, $SE = .10$, $t = .33$, $p = .746$, indicating that viewing positions following a corrective saccade did not differ between line length conditions.

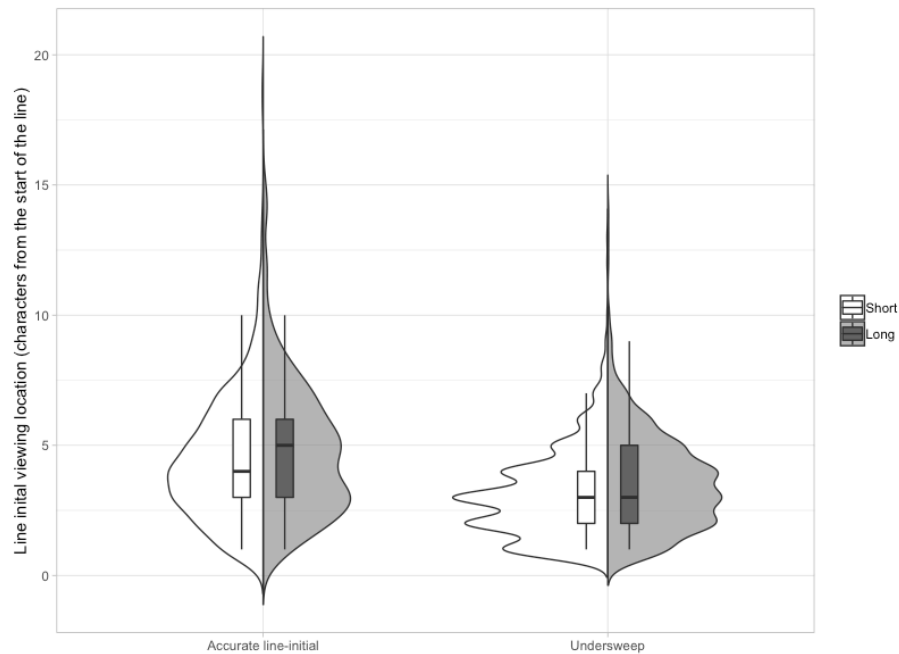


Figure 2.5. Split violin plot for line-initial viewing location (characters from the start of the line) in each line length condition for accurate line-initial and fixations following a corrective saccade towards the left margin. The distribution of line-initial viewing location for the short line condition is shown in white while the distribution of line-initial viewing location in the long line condition is shown in grey. Boxplots show the first quartile, median, and third quartile per fixation population.

2.3.2. Return-sweep fixation durations

Return-sweep fixation durations were compared to standard, intra-line reading fixations by coding a categorical variable with the following contrast values. “Intra-line” reading (non-return-sweep) fixations were coded as -1. Line-final fixations were coded as -0.5, accurate line-initial fixations as 0.5, and undersweep-fixations as 1. This coding scheme meant that “normal” reading fixations would represent the intercept to which the other “return-sweep fixations” were compared. To assess how fixation types differed between line length conditions, an additional fixed effect for condition was included and allowed to interact with fixation type. Means for each fixation population are shown in Figure 2.6.

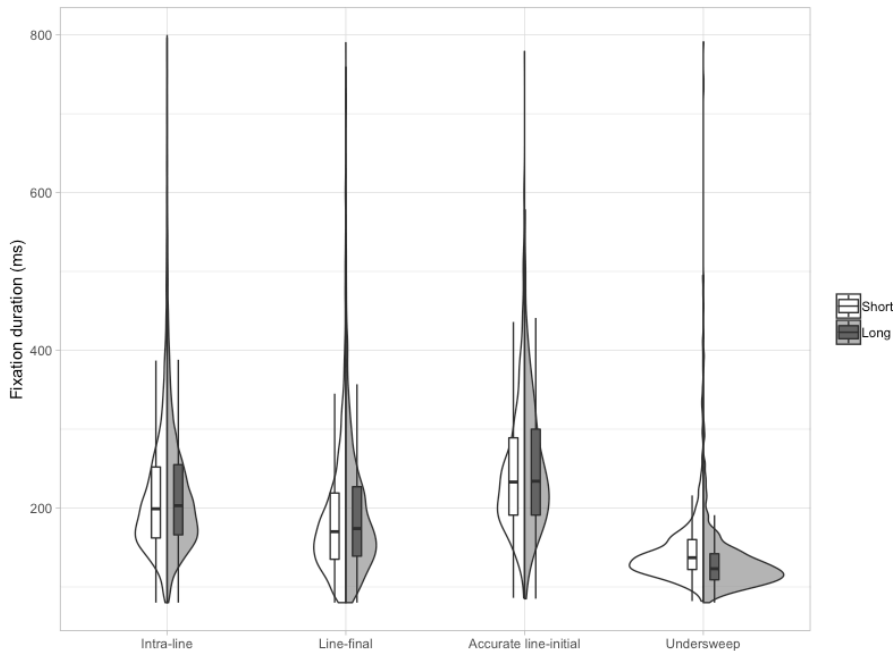


Figure 2.6. Split violin plot for the duration of each fixation population by line length condition. The distribution of saccade lengths in the short line condition is shown in white while the distribution of saccade lengths in the long line condition is shown in grey. Boxplots showing the first quartile, median, and third quartile per fixation population.

The model fit to log-transformed fixation duration data ($lmer(dv \sim \text{Fixation population} * \text{Line length} + (1 + \text{Fixation population} * \text{Line length} | \text{subject}) + (1 + \text{Fixation population} * \text{Line length} | \text{item}))$) indicated that, compared to intra-line reading fixations, line-final fixations were significantly shorter, $b = -.06$, $SE < .01$, $t = -$

20.79, $p < .001$. Accurate line-initial fixations were significantly longer than intra-line fixations, $b = .07$, $SE < .01$, $t = 12.57$, $p < .001$, while undersweep-fixations were shorter, $b = -.18$, $SE < .01$, $t = -48.96$, $p < .001$. There was no influence of line length on the duration of intra-line fixations, $b < .01$, $SE = .14$, $t = -.04$, $p = .999$, line-final fixations, $b < .01$, $SE < .01$, $t = -.78$, $p = .433$, or accurate line-initial fixations, $b < .01$, $SE < .01$, $t = .33$, $p = .743$. However, the difference between intra-line and undersweep-fixations was stronger in the long line condition, $b = .03$, $SE < .01$, $t = 7.01$, $p < .001$.

To examine the relationship between undersweep-fixation duration and line length condition, an additional model was fit to undersweep-fixation duration. Here the relationship between the distance that readers landed from the left margin, and undersweep-fixation duration was examined. Following the logic of Ohl et al. (2011), if a significant effect of condition is observed for undersweep-fixations when landing position is accounted for, it would indicate that the distance travelled by the saccade influences the duration of the undersweep-fixation. The model fit to log-transformed fixation duration data included fixed effects for distance of the fixation from the start of the line, line length condition, and their interaction. The converged model included intercepts for subjects and items (*lmer(dv ~ Landing position * Line length + (1 | subject) + (1 | item))*). Analysis indicated that the duration of undersweep-fixations did not differ between line length conditions, $b < .01$, $SE < .01$, $t = .46$, $p = .646$. As the landing position of the saccade shifted to the right, the undersweep duration decreased, $b = -.02$, $SE < .01$, $t = -14.75$, $p < .001$. The interaction between fixed effects did not reliably influence undersweep-fixation duration, $b < -.01$, $SE < .01$, $t = -.55$, $p = .582$. This indicated that the effect of landing position did not differ between line length conditions (see Figure 2.7.).

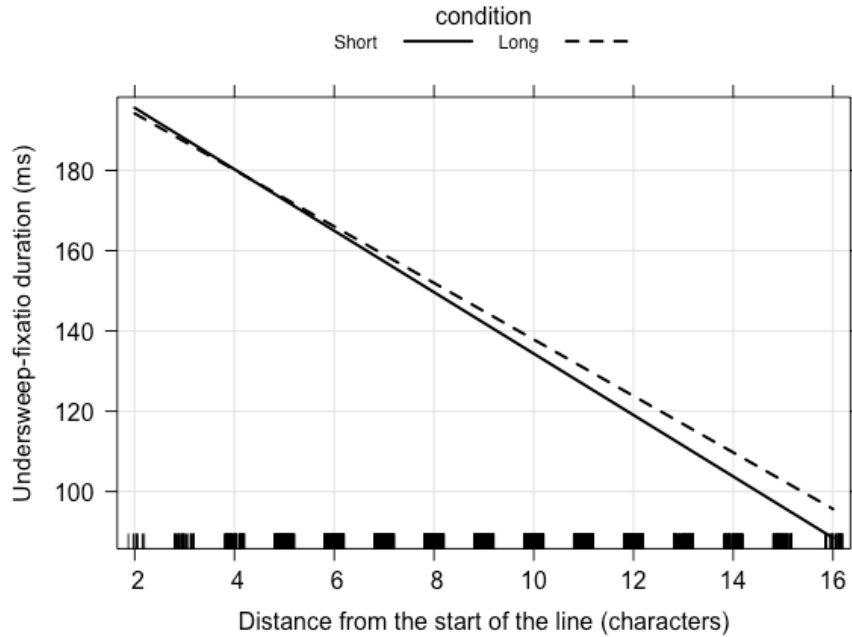


Figure 2.7. Undersweep-fixation duration (ms) as a function of the distance from the start of the line (characters) and line length. The solid black lines represent model estimates for the short line condition and the dashed black line represents model estimates for the long line condition.

2.4. Discussion

The main objective of the current study was to replicate earlier findings in relation to line length and return-sweep and corrective saccade parameters. In addition to replicating previous findings, several novel findings extend the published literature. The current study also aimed to examine the durations of fixations adjacent to return-sweeps. Consistent with the predictions set out in Section 2.1., accurate line-initial fixations were longer than intra-line reading fixations while line-final fixations were shorter. Undersweep-fixations were the shortest population of fixations.

With regards to line length, like Hofmeister et al. (1999), return-sweep launch sites were numerically further from the end of the line for shorter lines. However, statistical analysis indicated that this trend was not significant. This finding is of interest as it is indicative of a reader's need to progress towards the end of the line to continue lexical processing of the information in these locations. Where prior studies have reported only mean return-sweep launch sites, it could be suggested that readers avoid fixating these extremes to reduce the length of the

return-sweep. However, the current data lends no support for such an account. If such an account were correct, it would predict a greater reliance on parafoveal processing to encode information at the ends of longer line. As a result, this parafoveal processing would be evidenced by longer line-final fixations. Yet, line-final fixation duration did not differ between line length condition.

Previous investigations of return-sweep landing position have typically reported that return-sweep landing position is shifted to the right for longer lines (Heller, 1982; Hofmeister et al., 1999). In line with previous work, such an effect was observed. This effect, however, was largely driven by a shift in landing positions for undersweep-fixations while accurate line-initial fixations were uninfluenced by line length. From this finding, several conclusions about return-sweep landing positions can be made. First, readers generally target similar locations at the start of the line regardless of line length. The second is that error components of longer return-sweeps will result in a wider distribution of line-initial landing positions that is skewed to the right and varies as a function of line length (a proxy for saccade length). On occasions where the line-initial fixation does not land in a position that can afford processing of the information at the location of the saccade target, readers will require an additional corrective saccade to promote optimal processing of the line-initial information. Because of this greater variability in landing position, more corrective saccades will be required for longer lines.

While a comparison of means indicated a higher frequency of corrective saccades in the long line condition, analysis indicated that line length itself did not predict the likelihood of initiating a corrective saccade. Instead, this was predicted only by the distance at which the reader landed relative to the start of the line (which was more likely with longer lines). This provides clear evidence that corrective saccades are executed based on information available following a return-sweep rather than during return-sweep planning. Thus, it appears that the landing position of a return-sweep would mediate the relationship between line length and corrective saccade likelihood that has been frequently reported (Beymer, Russell, & Orton, 2005; Dutchicky & Kolers, 1983; Dyson & Kipling, 1998; Heller, 1982; Paterson & Tinker, 1940; Schneps et al., 2013; Tinker 1963). This finding is consistent with Findlay and Walker's (1999) model of saccade generation that assumes saccades are generated during the preceding fixation. This does not rule out the possibility that readers are more prepared to initiate a corrective saccade following a return-sweep.

Following corrective saccades, readers tended to position their point of fixation closer to the left margin than if the return-sweep landed in an accurate location. Given that accurate saccades tended to land further into the line, accurate line-initial fixations may only land in a “good-enough” position to enable linguistic processing rather than being a location that provides optimal viewing conditions for encoding. The decision of whether a location is “good-enough” would likely consider the cost of initiating a corrective saccade versus the cost of processing from a non-optimal location. We assume this would follow the calculation proposed by Becker (1972), whereby corrective saccades are made in response to a deviation of landing position from the saccade target which, once exceeding a certain threshold, triggers a corrective saccade. This threshold may represent the point at which moving the eyes to a new location outweighs parafoveal processing costs. This could explain the current finding that undersweep-fixation durations were shorter when the line-initial fixation landed further from the left margin. When readers land further from the start of the line/target location, the decision to trigger a corrective saccade happens faster, as acuity limitations in parafoveal vision would prevent word identification. However, when readers are partially able to encode information at the saccade target location, they may delay a corrective saccade while they estimate the cost of moving their point of fixation or remaining in that location and relying exclusively on parafoveal information to the left of fixation to aid lexical processing.

In relation to fixation durations, several existing findings were replicated. Line-final fixations were shorter than intra-line reading fixations while accurate line-initial fixations were longer. Existing accounts of these effects posit that shorter line-final fixations are the result of the processing of line breaks and return-sweep preparation (c.f. Abrams & Zuber, 1972). Longer accurate line-initial fixations are suggested to result from establishing a mode of grouped or strategic saccade programming and “start-up” effects (Al-Zanoon, Dambacher, & Kuperman, 2016; Kuperman et al., 2010; Pynte & Kennedy, 2008; Rayner, 1978), or increased vergence movements at the start of the line (Stern, 1978). However, the most parsimonious explanation for such an effect would be one that is consistent with Rayner (1977) and argues that differential processing strategies at line boundaries is responsible for the changes in fixation duration. As readers approach the end of the line, information in the parafovea will be reduced. As a result, the majority of processing occurring at the end of the line would occur foveally removing costs

associated with parafoveal processing from foveal processing. When readers arrive at the start of the line they have no preview of information in this location. As a result, the typical 30-50 ms advantage associated with parafoveal pre-processing will not be present. Data from the current study are consistent with this. Line-final fixations were, on average, 28 ms shorter than intra-line fixations, whereas accurate line-initial fixations were 31 ms longer. These means are on top of the 29 ms preview benefit that has been reported in a previous meta-analysis of preview benefit effects (Vasilev & Angele, 2017). Therefore, rather than be a pure artefact of oculomotor control and saccade planning, it is argued that these differences in fixation durations either side of the return-sweep are, at least in part, the result of attention and on-going linguistic processing.

Before moving on to our concluding remarks, it is important to note limitations of the current experiment. As identified in Section 1.3.4.1., a potential confound here results from the line length manipulation. Given that texts were identical between conditions, the line length manipulation meant that words could occur in different spatial locations between conditions. Differences in lexical properties of the text in these locations could have systematically influenced return-sweep behaviour in these locations. As with prior work, this could have influenced saccade targeting between conditions. Therefore, future work should maintain consistency in the information presented to readers at the locations in which return-sweep launch sites and landing positions are most likely.

2.5. Conclusion

In addition to replicating several previously reported findings, the results of the current study extend the previously reported literature. For instance, the finding that line length influences return-sweep landing position was replicated as was the finding that longer lines are associated with a higher frequency of corrective saccades. However, the current study further elucidates these findings. The current data suggests that the likelihood of making a corrective saccade is directly influenced by the landing position of the saccade rather than the distance traversed by the return-sweep itself. What is perhaps most intriguing from the current data is that accurate line-initial fixations may only be “good-enough” for processing. That is, they provide the reader with enough information to begin a left-to-right pass through the text rather than affording optimal conditions for word identification and

lexical processing. In relation to the pattern of fixation durations adjacent to return-sweeps, the current study empathises the utility of defining four specific populations of fixations for return-sweep research. The differences in durations at the very start and ends of lines are perhaps best explained in terms of parafoveal processing in the region they occur rather than a strict oculomotor planning account. However, future work is required to solidify this account and rule out alternative explanations for these differences. In the following chapter, Stern's (1978) assertion that longer line-initial fixations result from increased binocular disparity at the start of the line is examined as are the basic characteristics of binocular coordination for multiline texts.

Chapter Three

Binocular Coordination and Return-sweep Saccades

The following chapter has been submitted for publication as Parker, A. J., Nikolova, M., Slattery, T. J., Liversedge, S. P., & Kirkby, J. A. (2018). Binocular coordination and return-sweep saccades amongst skilled adult readers. *Journal of vision*. DOI: <https://osf.io/x2s5t/>

During reading, binocular coordination ensures that a unified perceptual representation of the text is maintained across eye movements. However, slight vergence errors exist. The magnitude of disparity at fixation onset is related to the length of the preceding saccade. Return-sweeps are saccadic eye movements that span a line of text and direct gaze from the end of one line to the start of the next. As these eye movements travel much further than intra-line saccades, increased binocular disparity following a return-sweep is likely. Indeed, increased disparity has been a proposed explanation for longer line-initial fixations. Thus, the current research sought to address the following questions: is binocular disparity larger following a return-sweep saccade than it is following an intra-line saccade, and is the duration of a line-initial fixation related to binocular disparity and coordination processes? To examine these questions binocular eye movements were recorded as participants read multiline texts. We report that, following return-sweeps, the magnitude of disparity at fixation onset is increased. However, this increased magnitude of disparity was unrelated to the duration of line-initial fixations. We argue that longer line-initial fixations result from a lack of parafoveal preview for words at the start of the line.

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Chapter Four

Return-sweeps and Lexical Processing

The following chapter is comprised of two papers. Both examine how lexical processing for the line-initial word is influenced by return-sweep execution.

The first paper has been published as Parker, A. J., Kirkby, J. A., & Slattery, T. J. (2017). Predictability effects during reading in the absence of parafoveal preview. *Journal of Cognitive Psychology*, 29, 902-911. DOI: 10.1080/20445911.2017.1340303

The predictability of upcoming words facilitates spoken and written language comprehension (see Kuperberg & Jaeger, 2016 for a review). One difference between these language modalities is that readers' routinely have access to upcoming words in parafoveal vision while listeners must wait for each word from a speaker. Despite readers' potential glimpse into the future, it is not clear if and how this information aids prediction. The current study manipulated the predictability of target words and their location on a line of text. Targets were located in the middle of the line (preview available) or as the first word on a new line (preview unavailable). This represents an innovative method for manipulating parafoveal preview which utilizes return sweeps to deny access to parafoveal preview of target words without the use of invalid previews. The study is the first to demonstrate gaze duration word predictability effects in the absence of parafoveal preview.

The second paper has been submitted for publication as Parker, A. J., & Slattery, T. J. (2018). Word frequency, predictability, and return-sweep saccades: Towards the modeling of eye movements during paragraph reading. *Journal of Experimental Psychology: Human Perception and Performance*. DOI: <https://osf.io/4bcuw/>

Models of eye movement control during reading focus on the reading of single lines of text. Within these models, word frequency and predictability are important input variables which influence fixation probabilities and durations. However, a comprehensive model of eye movement control will have to account for readers' eye movements across multi-line texts. Line-initial words are unlike those presented mid-sentence; they are routinely unavailable for parafoveal pre-processing. Therefore, it is unclear if and how word frequency and predictability influence reading times on line-initial words. To address this, we present an analysis of the Provo Corpus (Luke & Christianson, 2017) followed by a novel experimental study. We conclude that word frequency and predictability impact single-fixation and gaze durations on line-initial words. We also observed that return-sweep errors (undersweep-fixations) may allow for parafoveal processing of line-initial words prior to their direct fixation. Implications for models of eye movement control during reading are discussed.

Chapter Five

Undersweep-fixations and Lexical Processing

The following chapter has been accepted for publication as Slattery, T. J., & Parker, A. J. (2019). Return-sweeps in Reading: Lexical Processing Implications of Undersweep-fixations. *Psychonomic Bulletin & Review*. DOI: <https://osf.io/c7gjy/>

Models of eye movement control during reading focus on reading single lines of text. However, with multi-line texts, return-sweeps which bring fixation from the end of one line to the beginning of the next occur regularly and influence ~20% of all reading fixations. Our understanding of return sweeps is still limited. One common feature of return sweeps is the prevalence of oculomotor errors. Return sweeps, often initially under-shoot the start of the line. Corrective saccades then bring fixation closer to the line start. The fixation occurring between the undershoot and the corrective saccade (undersweep-fixation) has important theoretical implications for the serial nature of lexical processing during reading, as they occur on words ahead of the intended attentional target. Furthermore, since the attentional target of a return-sweep will lie far outside the parafovea during the prior fixation, it cannot be lexically pre-processed on the prior fixation. We explore the implications of undersweep-fixations for ongoing linguistic processing and models of eye movements during reading by analysing two existing eye-movement data sets of multiline reading.

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Chapter Six

Reading Development and Return-sweep Saccades

The following chapter is comprised of two papers. The first examines return-sweep and corrective saccade parameters in adults and children. The second examines undersweep-fixations and their implications for lexical processing in adults and children.

The first paper has been published as Parker, A. J., Slattery, T. J., & Kirkby, J. A. (2019). Return-sweep saccades during reading in adults and children. *Vision Research*, 155, 35-43. DOI: <https://doi.org/10.1016/j.visres.2018.12.007>

During reading, eye movement patterns differ between children and adults. Children make more fixations that are longer in duration and make shorter saccades. Return-sweeps are saccadic eye movements that move a reader's fixation to a new line of text. Return-sweeps move fixation further than intra-line saccades and often undershoot their target. This necessitates a corrective saccade to bring fixation closer to the start of the line. There have been few empirical investigations of return-sweep saccades in adults, and even fewer in children. In the present study, we examined return-sweeps of 47 adults and 48 children who read identical multiline texts. We found that children launch their return-sweeps closer to the end of the line and target a position closer to the left margin. Therefore, children fixate more extreme positions on the screen when reading for comprehension. Furthermore, children required a corrective saccade following a return-sweep more often than adults. Analysis of the duration of the fixation preceding the corrective saccade indicated that children are as efficient as adults at responding to retinal feedback following a saccade. Rather than consider differences in adult's and children's return-sweep behaviour an artefact of oculomotor control, we believe that these differences represent adult's ability to utilise parafoveal processing to encode text at extreme positions.

The second paper is currently in preparation for submission as Parker, A. J., Kirkby, J. A., & Slattery, T. J. (in prep). Undersweep-fixations during reading in adults and children. DOI: 10.31219/osf.io/z2sge

Return-sweeps take a reader's fixation from the end of one line to the start of the next. Return-sweeps frequently undershoot their target and are followed by a corrective saccade towards the left margin. The pauses prior to corrective saccades are typically considered to be uninvolved in linguistic processing. However, recent findings indicate that these undersweep-fixations influence skilled adult reader's subsequent reading pass across the line and provide preview of line-initial words. This research examined these effects in children. A children's reading corpus analysis revealed that words receiving an undersweep-fixation were skipped more and received shorter gaze durations. A subsequent eye movement experiment directly compared the eye movements of children and adults. While undersweep-fixations were not terminated based on lexical-frequency of the fixated word, both groups acquired information that informed their subsequent pass. We argue that this information is acquired preattentively. Additionally, fixation times on line-initial words were shorter following undersweep-fixations than if they had been directly fixated, indexing parafoveal preview during undersweep-fixations. However, the fixation after the undersweep-fixation showed no signs of spillover of lexical-frequency. We interpret this as evidence that attention during an undersweep-fixation is on a line-initial word rather than the fixated word.

Chapter Seven

General Discussion

The findings of the five empirical chapters presented in this thesis have implications for our understanding of return-sweep saccades, their trajectory, and, more generally, oculomotor control during reading. While each chapter dealt with relatively different aspects of oculomotor control and linguistic processing, the findings of all share several implications for the theoretical understanding of eye movements across multiline texts.

6.1. Basic overview of research findings

It is worth briefly summarising what exactly was investigated, found, and concluded in each chapter of this thesis. Chapter 2 aimed to replicate the existing literature showing that return-sweep and corrective saccade parameters are influenced by line length. In addition to replicating several previously published findings, the results of the current study extend the previously reported literature. The finding that line length influences return-sweep landing position was replicated as was the finding that longer lines are associated with a higher frequency of corrective saccades. However, the current study further elucidates these findings. For instance, the likelihood of making a corrective saccade was determined by the landing position of the saccade rather than the distance traversed by the return-sweep. In relation to the pattern of fixation durations adjacent to return-sweeps, chapter 2 emphasised the utility of defining four specific populations of fixations for return-sweep research. One causal explanation for these differences in fixation duration reflects differential processing of information in the parafovea. For instance, a lack of parafoveal processing for information at the start of the line following an accurate return-sweep explains why these fixations are longer than intra-line fixations. The work detailed in chapter 2 could not rule out Stern's (1978) account that binocular coordination processes are responsible for the increased duration of accurate line-initial fixations.

In chapter 3, the basic characteristics of binocular coordination during the reading of multiline texts were examined. By directly examining the influence of return-sweep saccades on measures of binocular coordination, it was possible to

empirically evaluate Stern's (1978) hypothesis that longer line-initial fixations are the result of binocular coordination processes. It was reported that, following return-sweeps, there was an increased magnitude of fixation disparity at fixation onset with the majority of fixations being uncrossed. Despite the increased magnitude of disparity at fixation onset, the magnitude of disparity was similar between fixation populations at fixation offset. While Stern argued that increased divergence during a return-sweep would result in longer line-initial fixation durations, the duration of these fixations was unrelated to disparity at fixation onset. That is, the magnitude of disparity at fixation onset did not influence line-initial fixation durations. Therefore, it was argued that longer line-initial fixations instead result from a lack of parafoveal preview for information at the start of the line during the preceding fixation.

In chapter 4, the influence of return-sweep execution on lexical processing was examined via two eye movement experiments and a corpus analysis. The main motivation behind this series of studies was to examine how lexical properties of the line-initial word influenced fixation durations on those words in the absence of parafoveal preview. In chapter 4 experiment 1, target words were embedded within passages of text so that they were positioned at the start or centre of a line. These target words were either a high- or low-cloze probability. Replicating prior work, fixation times were longer on line-initial words than those positioned within a line. Predictability effects were evident in readers gaze durations for words occurring at the very start of the line. However, there was no effect of predictability on first-fixation at the very start of the line indicating that lexical effects may only appear once readers have adjusted for non-optimal return-sweep landing positions. The corpus analysis attempted to examine the joint effects of lexical frequency and predictability on reading times of line-initial words. While these analyses indicated that fixations on line-initial words were shorter following an undersweep-fixation, the pattern of lexical effects were less clear. Therefore, a subsequent eye movement experiment addressed this. In chapter 4 experiment 2 it was reported that both lexical frequency and predictability impacted single-fixation and gaze duration. Thus, it was concluded that both frequency and predictability influence the reading of line-initial words when readers' return-sweeps land in a position that is optimal for linguistic processing.

Given the observation reported in chapter 4 experiment 2 that fixation time measures were shorter on line-initial words following an undersweep-fixation, a set

of corpus analyses reported in chapter 5 examined the possibility that readers may extract information at the point of an undersweep-fixation. Analysis indicated that when readers made an undersweep-fixation they were more likely to skip the word at that location during a subsequent pass. Furthermore, readers' subsequent gaze durations on these words were shorter than if they had encountered these words in a rightwards pass. This pattern was observed despite readers' undersweep-fixations being uninfluenced by the lexical properties of the fixated word. At the very least, these results indicate that readers attain and retain information acquired during an undersweep-fixation that is informative during a subsequent pass across the line. Though the nature of the information extracted during an undersweep-fixation remains unclear, it is proposed that readers extract letter identity information during a preattentive stage that influences encoding of these words during a subsequent pass.

In chapter 6, three eye movement studies were reported that examined return-sweep behaviour in skilled adult and developing readers. In the first, adults' and children's return-sweep and corrective saccade parameters were compared. In general, compared to adults, children launched their return-sweeps closer to the end of the line and landed closer to the start of the line. Children required more corrective saccades than adults. Together, these results indicate that children adopt a reading strategy in which they fixate more extreme locations on a line to compensate for reduced parafoveal processing. In a second study, it was reported that, like adults, children aged 10- to 11-years-old exhibited an undersweep preprocessing benefit. That is, increased skipping rates and shorter gaze durations on words that had previously received an undersweep-fixation. A final eye movement experiment examined the nature of attention during undersweep-fixations in both adults and children. By varying the frequency of word two on a line, it was possible to investigate the allocation of attention during an undersweep-fixation. While several findings were replicated (no effect of frequency on undersweep-fixation durations, and increased skipping and shorter reading times following an undersweep-fixation), it was reported that, like adults, children appeared able to acquire information from line-initial words during an undersweep-fixation. This processing was not influenced by the frequency of words at the point of an undersweep-fixation. Together these findings indicate that attention during an undersweep-fixation is directed towards its attentional target during reading in both adults and children.

6.2. Common implications

While the implications of these findings are discussed in the relevant empirical chapters, the ways in which these findings relate to each other may be less obvious. Therefore, the implications that this body of work has for lexical processing following a return-sweep and preview benefit is discussed below.

6.2.1. Return-sweeps and lexical processing

Line-final fixations are shorter than typical intra-line fixations (Abrams & Zuber, 1972; Hawley, Stern, & Chen, 1974; Rayner, 1977). These fixations appear uninfluenced by text degradation (Hofmeister, 1997) and are argued to prepare the oculomotor system for the execution of a return-sweep. Rayner (1977) proposed that this decrease in fixation duration at the end of the line is likely to reflect a lack of parafoveal processing in these locations. However, data presented in chapter 6 challenges such a view. The eye movement data in chapter 6 was recoded from children aged 6- to 9-years-old, who will have likely relied on foveal processing as opposed to parafoveal processing (cf. Häikiö et al., 2009). If a reduction in line-final fixation duration results from diminished parafoveal processing in skilled readers, children would show less of a reduction given that they will allocate more of their processing resources to the fixated word and considerably less to the parafoveal word. This was not the case. Instead, the reduction in fixation duration for line-final fixations relative to intra-line fixations was similar between adults and children. Therefore, the most parsimonious explanation for reduced fixation durations at the end of the line is that proposed by Hoffmeister (1997; see also Kuperman, Dambacher, Nuthmann, & Kliegl, 2010; Mitchell, Shen, Green, & Hodgson, 2008; Tiffin-Richards & Schroeder, 2018). That is line-final fixations prepare the oculomotor system to initiate a return-sweep rather than strictly being under direct cognitive control. Indeed, Hofmeister, Heller, and Radach (1999) provided data to suggest that readers plan their return-sweep during the line-final fixation. Hoffmeister et al. formatted texts to be left or right unjustified to assess the point at which return-sweeps are planned. Their logic was that if readers plan their return-sweeps as they progress across the line, left unjustified should cause disruption to reading as the target location of the return-sweep would not related the spatial map that readers had constructed. Yet, no disruption was observed. The authors argued that return-sweeps are programmed on the basis of visual information that is

available during the last fixation(s) on a line. Unless work directly addresses parafoveal processing at the end of the line, it is difficult to refute the oculomotor processing account of line-final fixations.

When return-sweeps are executed they generally follow one of two trajectories. On occasion, readers will land at a location that is close enough to the target of their return-sweep to enable readers to begin their rightwards pass. A second portion of return-sweeps will be immediately followed by a corrective saccade towards the left margin to afford processing of the information at the intended location of the return-sweep. Previous work has indicated that line length is closely related to this trajectory (Beymer, Russell, & Orton, 2005; Dutchnick & Kolars, 1983; Dyson & Kipling, 1998; Heller, 1982; Hofmesiter, Heller, & Radach, 1999; Paterson & Tinker, 1940; Schneps et al., 2013; Tinker, 1963). This finding was indeed replicated and presented in chapter 2. Rather than consider an increased frequency of undersweep-fixations a direct result of increased line length, the most parsimonious explanation is as follows. Longer lines will require a longer return-sweep. Because of increased systematic and random error (McConkie, Kerr, Reddix, & Zola, 1988), these longer saccades will show a wider distribution of landing sites with an extended right tail. These saccades will necessitate additional corrective saccades to encode information at the start of the line when the line is long. The corrective saccade is unlikely planned in parallel with the return-sweep and is instead executed based on retinal feedback when readers land at the start of the line (c.f. Becker, 1972). Consistent with this, the landing position of the return-sweep is reported to influence the likelihood of initiating a corrective saccade (see chapters 2 and 6). After executing a corrective saccade, readers' subsequent fixations typically land closer to the start of the line than accurate line-initial fixations. It is concluded that rather than being optimal for word recognition, accurate line-initial fixations are those that land in position that is good-enough to afford lexical processing of information at the start of the line. The decision of whether a location is good-enough would likely consider the cost of initiating a corrective saccade versus the cost of processing from a non-optimal location.

When return-sweeps are accurate and do not require a corrective saccade, line-initial fixation are longer than intra-line reading fixations (Rayner, 1977). Stern (1978) proposed that this increased duration is the result of the saccadic orienting system having to resolve increased disparity at the very start of the line. Indeed,

Stern (1978) was correct in proposing that there is increased fixation disparity at the start of the line. However, as reported in chapter 3, this magnitude of disparity did not influence the duration of accurate line-initial fixations ruling out a binocular account of inflated line-initial fixations. Instead, an account in which readers must compensate for a lack of preview benefit for the line-initial word is advocated. During intra-line reading, readers are able to, and benefit from, parafoveal processing (see Schotter, Angele, & Rayner, 2012, for a review). This of course has implications for reading at the start of the line. The pattern of data reported in chapter 4 indicates that despite a lack of preview for the line-initial word, lexical variables do influence fixation times on these words as they would in a typical left-to-right pass. One small caveat is that readers must land in a position that is optimal enough to afford word processing. In chapter 4 experiment 1, it was reported that predictability effects were absent in first-fixation duration on line-initial words. Indeed, in experiment 2, these effects were present when readers had landed in a position that was optimal enough to afford word processing (i.e. single-fixation duration) or after correcting for non-optimal landing positions (i.e. gaze duration).

Above it is suggested that lexical processing can begin when readers land optimally on the line-initial word. As indicated in chapter 4 experiment 2, lexical processing for line-initial words can commence during undersweep-fixations. One explanation for this effect is that undersweep-fixations represent a mislocated fixation (Drieghe, Rayner, & Pollatsek, 2008). While undersweep-fixations may not be on the target of the return-sweep, attention may be on the target. This decoupling of eye movements and attention would enable readers to begin to process line-initial words prior to direct fixation. Although, the precise nature of information extracted from line-initial words during undersweep-fixations is unclear. When readers make an undersweep-fixation, they often skip that word during subsequent reading. When these words are fixated during a rightwards pass, measures of first-pass reading time are shorter compared to cases where they are fixated following an accurate line-initial fixation on the line initial word. One candidate explanation assumes that readers acquire letter identity information that survives masking across fixations. This acquisition is likely to occur very early (i.e. a preattentive stage) during the course of a fixation while readers conduct a cost/benefit analysis in the decision to execute a corrective saccade towards the left margin.

6.2.2. Preview benefit and predictability effects

In chapter 4 a new methodology for investigating parafoveal preview effects during reading was established. This methodology enables researchers to examine the processing of target words without having to consider the costs of an invalid preview (see Vasilev, Slattery, Kirkby, & Angele, 2018 for a discussion). By comparing trials in which undersweep-fixations enable preview of the line-initial word with those where the target was accurately fixated, researchers gain an estimate of the preview benefit. This way of assessing the preview benefit should be seen as yet another valuable tool for studying eye movements during reading.

Our implementation of this novel methodology revealed that predictability effects could be observed in the absence of parafoveal preview. This stands in stark contrast to a large body of evidence which suggests that predictability effects are dependent on the presence of orthographic information that is at least visually similar to the target (see Staub, 2015 for a review). Our explanation reconciles these conflicting findings and is one based on Bayesian belief updating (Hale, 2003; Levy, 2008). It is reasoned that when readers are able to obtain information in the parafovea they make use of this information to update their ongoing representation of the text. Within Levy's (2008) framework, predictability effects arise in a graded manner based on prior beliefs of sentential meaning. When readers are provided with an invalid cue, like they are in many studies typically investigating the predictability preview interaction, beliefs are shifted in a different direction and the target word becomes less predictable. In contrast, when there is no preview (in the case of line-initial words), beliefs are maintained until the word is available in foveal vision (i.e. after the return-sweep). As a result, beliefs are maintained and predictability effects remain so long as this word matches readers' beliefs.

6.3. Assessing E-Z Reader and SWIFT

As they are currently implemented, models of eye movement control during reading are only capable of simulating behaviour for single lines of text. In Section 1.4. of this thesis, several hypotheses were made about how the current architecture of E-Z Reader and SWIFT could be extended to account for return-sweeps as parsimoniously as possible given their current implementation. Here, these are hypotheses summarised for the reader and the main challenges for each model are highlighted.

6.3.1. E-Z Reader

During single line reading, E-Z Reader assumes that when lexical processing (L1 and L2) is complete for word n , attention moves to word $n+1$ and readers begin processing $n+1$ in parafoveal vision. Viewing return-sweeps as any other inter-word saccade with the exception that the shift in attention to the first word of the next line does not result in parafoveal processing for the line-initial word may be sufficient to explain several findings reported throughout this thesis. Under this additional assumption:

1. Lexical processing for line-initial words would occur only after return-sweep execution and the word is available in (para)foveal vision.
2. Fixations on line-initial words would be longer than those on intra-line words.
3. Fixation times on line-initial words would be reduced if preceded by an undersweep-fixation due to the availability of preview benefit following these fixations.
4. Attention would be on the line-initial word during an undersweep-fixation, meaning that undersweep-fixations would not be terminated based on lexical properties of fixated word.
5. Effects of word frequency and predictability would remain the same as for other words.

Throughout this thesis, evidence was found to support all predictions. As observed in chapters 2, 3, 4, and 6, accurate line-initial fixations were longer in duration than intra-line reading fixations. As reported in chapters 4 and 6, single-fixation and gaze durations on line initial words were also shorter if they had been preceded by an undersweep-fixation. Chapters 5 and 6 reported that undersweep-fixations were not influenced by lexical qualities of the fixated word. The pattern of data presented in chapter 4 also indicated that word frequency and predictability effects for line-initial words were similar to those for line-internal words. Together this simple additional assumption— that lexical processing (L1 and L2) of words on a line not occur until that line had been fixated— would be able to explain a number of findings in relation to the processing of line-initial words.

At current, E-Z Reader is unable to explain the finding that readers' fixations at the very end of a line are shorter than those occurring midline. E-Z Reader may

also have difficulty explaining the findings reported in chapters 5 and 6: that readers appear able to acquire meaningful information from words at the point of an undersweep-fixation. If readers are merely extracting letter identities which inform later reading, the acquisition of information during EZ Reader's preattentive stage may simulate a similar pattern of data. However, if readers are engaging in lexical processing, this may result in E-Z Reader relaxing its strictly serial assumption about the nature of attention for this certain group of fixations, or it may have to incorporate several additional assumptions about attention and lexical processing following a return-sweep.

6.3.2. SWIFT

SWIFT requires words to have activation in order for them to be selected as saccade targets. However, activation only builds for words when words are in the attentional window. Given that the target of a return-sweep falls well outside of this window during normal reading, SWIFT will require modifications to its core assumptions or a new specific assumption to model return-sweeps.

Assuming these modifications did not change the overall architecture of SWIFT, several predictions were made in chapter 1. First, SWIFT would predict that return-sweep fixations would not differ from intra-line reading fixations as all fixation are governed by a random timer. Of course, the data presented throughout this thesis do not support such a prediction. Instead, fixations prior to a return-sweep are shorter while accurate line-initial are longer. To model the observed data a mechanism may be included where the building of activation is delayed at the start of the line. Second, the assumptions outlined in the SWIFT model would lead to the prediction that activations would build from zero when readers land at the start of a line. As a result, refixations would be observed frequently. Indeed, a substantial number of return-sweeps are followed by an intra-word corrective saccade (see chapter 6). Third, it would lead to the prediction that word frequency effects would be identical for line-initial words and those presented midline as a result of word frequency only influencing maximum activation and does not influence changes of activation over time. Indeed, with an exception to gaze duration in our analysis of the Provo Corpus in chapter 4, we find evidence in support of this prediction.

While SWIFT will struggle incorporating the implementation of return-sweep execution, its assumptions underlying the allocation of attention may explain what E-Z Reader cannot. SWIFT assumes that readers are able to process all

information in the perceptual span whereas E-Z Reader assumes attention to be allocated in a serial manner. As a result, SWIFT may be better suited to explain the finding that there is an increased rate of skipping for words receiving an undersweep-fixation prior to the rightwards pass as SWIFT posits that readers acquire information out of its canonical order so long as it is within the attentional window. Indeed, within SWIFT it is plausible for readers to process information at the point of an undersweep-fixation without processing the line-initial word. However, this should not distract from the fact that SWIFT, as currently implemented, does not predict the most robust finding from this thesis: that line accurate line-initial fixations are longer than intra-line reading fixations.

6.4. Avenues for future research

The avenues for future research are now considered. They are generally aimed at further exploring return-sweeps so that computational models of eye movement control during reading can accurately model eye movement behaviour at line boundaries.

First, it is argued that line final-fixations largely serve the purpose of planning return-sweeps rather than being directly involved in lexical processing. It would be interesting to see how lexical properties of the line-final word (i.e. lexical-frequency) modulate line-final fixation durations. As discussed throughout this thesis, there is evidence to suggest that line-final fixations may not be under direct lexical control. An absence of a frequency effect for these fixations would strongly indicate this. Of course, if a frequency effect was observed for line-final fixations, it would not strictly indicate that line-final fixations were involved in lexical processing as spill-over effects may occur from the previous fixations. Therefore, a carefully designed study would provide the means to disentangle potential spillover effects from genuine frequency effects for line-final fixations.

From this thesis, it is evident that accurate line-initial fixations are longer than intra-line fixations. While chapter 3 clearly rules out a binocular disparity account of longer line-initial fixations, two remain. While each empirical chapter leans towards a lack of preview as the most parsimonious explanation, it is possible that longer line-initial fixations result from oculomotor programming. At current there is insufficient data to warrant a decisive conclusion on the cause of these longer fixations. Therefore, a series of experiments aimed at investigating longer line-initial fixations are suggested. The first experiment would assess the assertion

that longer line-initial fixations are the result of grouped saccadic programming for fixations across the line (c.f. Rayner, 1978). To accomplish this, participants would read two lines of text where the second line would be varied in length (short vs. long). If longer line-initial fixations are the result of programming saccades, longer lines would necessitate longer line-initial fixations while readers plan their subsequent eye movements across the line. In a second experiment, participants would engage in the scanning of Landolt Cs. Such a task would remove the need to engage in linguistic processing, thus removing the cost of a lack of parafoveal preprocessing. If, under these circumstances, line-initial fixations were reduced it would provide evidence for a linguistic preprocessing account of longer line-initial fixations.

A further avenue for future work would be to assess the type of information that readers acquire during an undersweep-fixation. In chapters 5 and 6 data pertaining to both adults and children are reported which find that both groups could attain information during an undersweep-fixation. Therefore, it is vital to assess the type of information extracted from the fixated word. One possibility is that readers access phonological and orthographic codes. To assess this possibility, a variation of the boundary paradigm could be utilised where the boundary is placed between words one and two on a line. The second word on a line will change from a preview string to a target word when a corrective saccade takes the eyes from word one to word two. The preview would be an accurate, an orthographically/phonologically/semantically related or unrelated word. By comparing subsequent reading times in cases where this word received an undersweep-fixation or did not, the type of information that readers extract during an undersweep-fixation can be assessed.

6.5. Final Comments

It is hoped that this final chapter has illustrated the important theoretical contributions of the work presented throughout this thesis. While these chapters dealt with somewhat varied topics, they all have significant implications for our understanding of return-sweep saccades, especially in terms of return-sweep trajectories and their influence on linguistic processing. Furthermore, it should be clear that these studies provide several benchmark findings from which future studies can be developed far beyond what has been presented in this thesis, in order

to further increase our understanding of oculomotor control and linguistic processing during the reading of multiline texts.

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