The Eye-voice Span and Return-sweeps during Oral Reading: Developmental Implications

by

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Copyright statement

Abstract

Learning to read begins with connecting the speech sounds and written symbols of a language through overt pronunciation. With time, children blend multiple sounds, starting with reading single words and proceeding to read sentences and passages spanning multiple lines. Although, silent reading is the hallmark of skilled reading, children often read aloud for several years after reading instruction begins. Recent eye movement reading research has focused on silent reading of single line texts with less known about reading passages aloud. Therefore, the present thesis investigated the mechanisms associated with reading multiline texts aloud.

The current state of knowledge regarding eye movements during reading was reviewed in Chapter 1. The first experiment in Chapter 2 examined differences between eye movements at line boundaries in oral and silent skilled reading. This experiment revealed greater costs for oral reading across lines compared to reading within lines. This cost was proposed to be associated with the distance the eyes are ahead of the voice (i.e., the *eye-voice span*; EVS) when making return-sweeps (eye movements that take our gaze from the end of one line to the beginning of the next line). Therefore, the second experiment, presented in Chapter 3, was designed to examine the development of the EVS across grades three, four and five; and probe the sensitivity of the EVS to sub-lexical phonological codes i.e., syllables. Grade five children had larger spans and were more proficient readers, according to assessments of reading skills, than grade four children. Whereas grades three and four children had similar spans and proficiency levels indicating that developmental EVS changes are primarily driven by reading proficiency. In addition, syllable sensitivity was only found in gaze duration but not the EVS.

The multiline experimental stimuli presented in Chapter 3 allowed the examination of the modulation of the EVS at line boundaries in Chapter 4. This study confirmed that the greater oral reading cost found in Chapter 2 was related to increased modulation of the EVS by the fixation durations around line boundaries (i.e., before and after the return-sweep saccade). Considering the relationship between reading proficiency and the EVS (Chapter 3) and impact of the EVS on eye movements (Chapter 4), in Chapter 5, we examined reliability and individual differences in the EVS and its modulation. This study showed that the EVS can provide additional information about the reading process which was not captured by the eye movements alone.

The typical EVS indicates that the fixated word will likely differ from the articulated word, therefore, the final study in Chapter 6 explored bi-directional lexical effects on articulation and fixation durations. This study revealed that high frequency articulated words reduce fixation times on concurrently fixated words and vice versa. Together, these findings provide a wholistic understanding of children's reading and shed light on the mechanisms that are responsible for increased oral reading times.

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 on page xvi. The main text in each chapter is presented as exact replications of the published, submitted and to-be submitted manuscripts. However, slight modifications were made to the unpublished chapters for coherence.

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List of Abbreviations

AoA: Age of Acquisition

ANOVA: Analysis of variance

CPWD: Children's Printed Word Database

EVS: Eye-voice span

d: Cohen's d effect size

FFD: first fixation duration

GD: Gaze duration

(G)LMM: (Generalised) Linear Mixed Models

IQ: Intelligence Quotient

LQH: Lexical Quality Hypothesis

SD: Standard deviation

SE: Standard Error

RAN/RAS: Rapid Automatized Naming/ Rapid Alternating Stimulus

TOWRE: Test of Word Reading Efficiency

WIAT: Weschler's Individual Achievement Test

WASI: Weschler's Abbreviated Scale of Intelligence

TVT: Total Viewing Time

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CHAPTER 1: Introduction and Literature Review

Learning to read involves making connections between the speech sounds of a language and the symbols designed to represent those sounds (Ehri, 2005a). In the early years of reading instruction, the mastery of sound-letter correspondences is hinged on the oral production of such sounds while looking at the letters (Taylor & Connor, 1982). Therefore, reading aloud helps children become proficient readers as they transition into silent reading. However, before making this transition, they often engage in oral reading, especially in primary grades. Oral reading helps children develop the ability to decode words rapidly and accurately to ensure that enough cognitive resources are available for comprehension (Petscher & Kim, 2011). In line with these, many studies have reported a close relationship between the elements of oral reading fluency (speed, accuracy, and expressiveness) and reading comprehension (Denton et al., 2011; Fuchs et al., 2001; Kim et al., 2010; Kim et al., 2012). Furthermore, the importance of oral reading is underscored in its use as the major indicator of fluency up to the 8th grade (Hasbrouck & Tindal, 2006; Rasinski & Hoffman, 2003).

Given the importance of oral reading in helping children learn to read and assessing reading competence, it is surprising that the number of developmental eye-tracking studies using oral reading is relatively less than studies using silent reading. Investigating oral reading using an eye-tracking methodology has the potential to explain developmental processes in reading acquisition as it represents an ecologically valid assessment of children's reading. More so, considering that children rarely ever read aloud in single lines, it is surprising that sparse research exists on how children navigate between one line to another when reading aloud.

Consequently, this thesis aims to uncover eye movement behaviour as related to both oral reading and reading across line boundaries. This aim will be achieved by exploring the eye-voice span (EVS), the distance between the eye and the voice during oral reading, and return-sweep saccades, the eye movements that take our gaze from the end of one line to the beginning of the following line. The following are the specific objectives of this thesis:

- To investigate reading modality differences in eye movements across line boundaries.
- To investigate developmental differences in the EVS and whether the EVS is sensitive to sub-lexical processing units.

- To clarify the relationship between the EVS and eye movements across line boundaries.
- To consolidate our understanding of the EVS using an individual differences approach in developing readers.
- To examine bidirectional lexical influences on eye movements and speech production during oral reading.

The introduction begins with an overview of basic characteristics of eye movements during reading. Following on that, I review reading modality differences, reading ability differences, and how word characteristics influence eye movement behaviour. Subsequently, I examine theories that have served as a framework for the research questions and conclude with a thesis summary.

1.1 Eye movements during Reading

Over the years, research has shown that eye movements are a reliable and valid measure for understanding cognitive skills such as reading (Liversedge & Findlay, 2000). Reading comprehension, a higher-order cognitive skill, begins by processing letter information from individual words across a page of text (Gough & Tunmer, 1986; Karageorgos et al., 2020). Readers achieve this initial step through visual perception enabled by continuous eye movements (Paradiso et al., 2012). Therefore, eye movements allow the visual uptake of orthographic features of print, which the brain decodes into phonological and semantic codes to make meaning (Grainger & Hannagan, 2014). Researchers use behavioural measures such as reaction time and accuracy during naming, lexical decision, and semantic categorisation to understand the reading process. However, these measures are single end-point estimates and may not capture many important reading processes. Eye movement measures, on the other hand, provide a window into the moment-by-moment cognitive processing of text (Just & Carpenter, 1980; Starr & Rayner, 2001). Through the use of multiple eye movement measures (as will be explained later in this section), researchers can gauge the time course of linguistic processing (Liversedge et al., 1998) of target words (e.g., Rayner, Reichle, et al., 2006), regions of text (e.g., Rayner, Chace, et al., 2006), and entire texts (e.g., Mason et al., 2013).

1.1.1. Basic Characteristics of Eye Movements during Reading

Eye movements are important because only information falling on the fovea, 2 degrees of visual angle, around the fixation point, can be seen with the highest resolution or clarity

(Rayner & Bertera, 1979). Beyond the fovea is the parafovea, which is 5 degrees around the fixation location. In this region, visual acuity drops as the distance from the fixation increases (Schotter et al., 2012). Visual acuity is the lowest in the peripheral region, which lies beyond the parafovea (Rayner, 1998). Therefore, saccades are needed to align the object of our attention with the fovea. *Saccades* are ballistic movements that take our gaze from one point in the text to another (Rayner, 1998; Zachary Jacobson & Dodwell, 1979). They are typically measured in character spaces or degrees of visual angle and are 8 character spaces on average in skilled adult readers (Rayner, 1986). In between saccades are *fixations*, periods when the eyes pause for about 250ms to encode new text information (Rayner, 1977). Saccades and fixations are the basic eye movement metrics from which all other measures are derived. These two measures have been known as the *where* and *when* of eye movements or *spatial* and *temporal* measures.

Where do readers target their saccades? Research shows that most saccades are targeted at word objects. Specifically, readers' initial landing position in a word is near the left of the word centre. This position is called the Preferred Viewing Location (PVL; Rayner, 1979). However, the centre of the word where recognition is optimized is known as the Optimal Viewing Location (OVL; O'Regan, 1990; O'Regan & Jacobs, 1992). Readers use spatial information such as the location of word boundaries (Pollatsek & Rayner, 1982) and word length (Joseph et al., 2009; Rayner, 1979) available in the parafovea during a fixation to target their saccades. For example, longer words are more likely to be fixated and refixated, and shorter words are likely to be skipped (Brysbaert & Vitu, 1998; Joseph et al., 2009; Rayner, 1979; Rayner et al., 2011). Skipping occurs when words to the right of a fixation have been parafoveally previewed (Reichle et al., 1998) or are predictable from prior context (Rayner et al., 2011) and therefore, may not require direct fixation. However, readers may fixate skipped words during second pass reading, i.e., regression (Brysbaert & Vitu, 1998; Drieghe et al., 2004). Regressive saccades occur about 10-15% of the time (Rayner, 1998). They serve to position the eyes on earlier text portions due to incomplete word recognition processes or comprehension difficulties (Inhoff et al., 2019; Vitu, 2005). Another kind of saccade that I will return to in the next section (1.1.2.), is the return-sweep saccade. This much less studied saccade takes our gaze from the end of one line to the beginning of the next (Parker et al., 2017; Parker, Nikolova, et al., 2019; Parker, Slattery, et al., 2019).

When do readers leave a fixated location? Like saccades, visuomotor factors such as word length influence fixation durations. Longer words received longer fixations compared to shorter words (Rayner et al., 2011). However, linguistic variables are heavily

involved in how long to fixate a word. Words with higher frequency receive shorter fixations than words with lower frequency (Hyona & Olson, 1995; Just & Carpenter, 1980; Rayner & Duffy, 1986). I will revisit this in section 1.4 when reviewing how word-level variables influence eye movements. Similar to spatial measures, fixations also have multiple measures (Liversedge et al., 1998; Raney et al., 2014; Rayner, 1998). Eye movement reading research often report *first fixation duration* (FFD), *gaze duration* (GD), and *total viewing time* (TVT) on target words or regions. The first fixation duration represents a reader's initial lexical processing of the word and usually reflects experimental manipulations such as word frequency or length. However, because some words receive more than one fixation, another critical measure is gaze duration which sums all the first pass fixations on a word before fixating a different word or region (Liversedge et al., 1998; Rayner, 1998). This measure is particularly important for developing readers who are more likely to refixate words (Blythe et al., 2011). While first fixation and gaze duration are considered early measures of reading, total reading time is considered a late measure reflecting semantic integration of the word or region of text. This measure includes first pass reading time and any re-reading time.

Although words are processed in serial order, according to the E-Z model (Reichle et al., 2012), readers can extract information from words beyond the foveal word during a single fixation. This kind of processing is called parafoveal pre-processing. According to the E-Z reader model, parafoveal pre-processing occurs because after lexical processing of the current word is completed, attention can be allocated to the next word (n+1) before a saccade is executed to it. Typically, this kind of processing occurs for words within the perceptual span. Alternatively, another model called SWIFT (Saccade Generation With Inhibition by Foveal Targets; Engbert et al., 2002), explains parafoveal pre-processing as being due to parallel activation of words within the perceptual span (see section 1.5 for more details). The perceptual span is the entire region from which useful information is extracted (Choi et al., 2015; Rayner, 1997; Rayner, 1998). Additionally, it is asymmetrical in the reading direction (i.e., 3-4 characters left and 14-15 characters right of fixation in skilled readers; Rayner, 1986; Rayner, 1998; Reichle et al., 2003). The use of gaze-contingent displays has made the study of the perceptual span possible. Such displays allow stimuli presentation to be dependent on where the reader's gaze is. For example, the moving window paradigm (McConkie & Rayner, 1975) manipulates the amount of information readers can see based on the fixation point, while other parts of the text are masked. The window of unmasked text moves continuously through the text as readers move their gaze.

Another gaze-contingent display is the boundary change paradigm (Rayner, 1975). In contrast to the moving window paradigm, all words but one target word are unmasked. In this paradigm, experimenters manipulate the information in the parafovea (i.e., right region) with either a similar or dissimilar preview (typically a string of letters). When gaze crosses an invisible boundary before the manipulated region, i.e., the pre-target word, the actual word appears or is unmasked. If a similar preview was present before crossing the boundary, the fixation duration on the target word is shorter than if it were a dissimilar preview. This processing advantage has been termed the parafoveal preview benefit (see Schotter et al., 2012 for a review; Vasilev & Angele, 2017). With these types of paradigms, researchers have been able to uncover the nature and amount of information that is acquired foveally and parafoveally during a single fixation.

Taken together, the measures and methods described above have provided eye movement researchers with standards for conducting reading experiments, analysing, and presenting data in a structured, comparable, and reproducible manner. In the next sections, I highlight the characteristics of eye movement patterns across line boundaries.

1.1.2. Eye Movements across Line Boundaries

Much of what is known about eye movements i.e., saccades and fixations, during reading is limited to single-line studies. Although eye movements are used to understand language processing using multiline text, less attention is given to understanding the eye movements that occur between lines. However, everyday reading occurs over several lines, whether reading recipe instructions on a pack of egg noodles or studying for an upcoming examination. These text types involve a different kind of forward saccade discussed in the previous section. During passage reading, the eyes employ long reading saccades that move in a different direction to the reading direction, i.e., right to left. These saccades are called return-sweep saccades that take our gaze from the end of one line to the next line. Accumulating evidence suggests that these saccades are different from intra-line saccades that occur within the line.

First, the target of the return-sweep saccade is usually outside parafoveal vision unlike intra-line saccades (Parker et al., 2017; Parker, Slattery, et al., 2019; Slattery & Vasilev, 2019). Second, while reader's target intra-line saccades toward word centres (Joseph et al., 2009; Rayner, 1979; Rayner, 2009), return-sweep saccades are targeted towards an area near the left margin that optimizes word recognition processes regardless of line-initial word length (Slattery & Vasilev, 2019). Third, research has shown that the travel distance of the return-sweep makes it susceptible to larger errors compared to intra-

line saccades (Becker & Fuchs, 1969). Typically, most return-sweep saccades launch and land five to seven characters away from either margin of successive lines. However, some land far away from the margin resulting in leftward corrective saccade errors that occur 40-60% of the time. These corrective saccades serve to bring the eyes to an optimal location for word identification. Additionally, there is evidence that the fixation before the corrective saccade allows for the processing of the fixated word (Parker et al., 2020; Parker & Slattery, 2019) and parafoveal processing of line-initial words (Slattery & Parker, 2019).

Fourth, the adjacent fixations of return-sweep saccades differ in duration and are likely driven by different processes compared to intra-line fixations. The primary function of intra-line fixations is to extract linguistic information and enable word recognition. However, line-final fixations (preceding return-sweep saccades) are also involved in oculomotor planning and execution of the return-sweep saccade (Kuperman & Van Dyke, 2011; Mitchell et al., 2008). Consequently, this fixation is shorter than intra-line fixations (Hofmeister et al., 1999). Although, shorter line-final fixations could also result from a lack of parafoveal information (Rayner, 1977).

Fixations that follow the return-sweep saccade could belong to one of two categories: accurate line-initial fixations and undersweep fixations. Accurate line-initial fixations are usually longer than intra-line fixations and followed by rightward saccades in the reading direction. Undersweep fixations, on the other hand, are the shortest of all fixation types and are followed by leftward corrective saccades against the reading direction. Accurate line-initial fixations are longer that intra-line fixations because words receiving these fixations have been denied preview opportunity (Parker et al., 2017; Parker, Slattery, et al., 2019). Alternatively, the length of this fixation could result from group saccade planning processes on the new line (Kuperman et al., 2010; Parker, Slattery, et al., 2019). Undersweep fixations, on the other hand, are thought to arise due to retinal feedback from landing in a suboptimal location (Abrams & Zuber, 1972; Hofmeister et al., 1999).

The theoretical distinction between these fixation types reveals how the oculomotor system adjusts to ensure maximal information uptake based on the amount of information available at different text locations including line boundaries. Unfortunately, how this adjustment occurs is largely limited to skilled silent reading. Therefore, we are unaware of how the demands of oral reading and the EVS may be involved in these processes.

1.2. Eye Movements and Reading Modality

Early research examined eye movements during oral reading, but few studies have focused on it in recent years especially in skilled readers. This is likely because oral reading represents a less mature way of reading that is more common with children or less skilled readers. The central processes underlying oral and silent reading operate similarly, i.e., visual processing of letter features and lexical identification of words (Juel & Holmes, 1981; Schilling et al., 1998). However, oral reading involves activating multiple processes with the end goals of comprehension and oral fluency. Although inner speech occurs during silent reading (Abramson & Goldinger, 1997; Filik & Barber, 2011; Huestegge, 2010), the need to plan and overtly produce speech during oral reading results in several differences. For example, van den Boer et al. (2014) showed that phonological awareness related strongly to oral and silent reading. However, rapid automatized naming (RAN) skill involving overt articulation was more strongly related to oral than silent reading. van den Boer et al. (2014) interpreted this finding as resulting from shared phonological representation in both modalities but a specific phonetic representation in oral reading (Levelt et al., 1999).

Research findings about differences in comprehension due to reading modality are equivocal. Some argue that oral reading is superior in lower grades than silent reading and detrimental in higher grades (Elgart, 1978; Prior et al., 2011). Younger readers may benefit from oral reading because it gives the opportunity to monitor their articulation. The feedback they receive from articulation may serve to enhance comprehension (Kragler, 1995). Older readers, on the other hand, may need to devote extra attention to production processes limiting the attention given to comprehension processes (Jones & Lockhart, 1919). Still, others have found no differences between oral and silent reading comprehension scores (Holmes, 1985; Schimmel & Ness, 2017). Some other studies emphasise differences in speed rather than differences in comprehension (Juel & Holmes, 1981; McCallum et al., 2004). Speed differences occur primarily because oral reading hinges on the speech motor system, which is typically much slower than the rate of visual or linguistic processing (Ashby et al., 2012; Inhoff et al., 2011). Given these differences, I begin this section by reviewing the basic differences between eye movements during oral and silent reading.

1.2.1. Basic Eye Movement Differences between Oral and Silent Reading

Generally, oral reading takes more time than silent reading. Eye movement records show that, on average, fixation durations are 50ms longer, and saccades are 2-character spaces

shorter during oral reading than silent reading. (Anderson & Swanson, 1937; Rayner, 1977; Rayner, 1986; Rayner, 1998; Rayner, 2009). Additionally, there is an increase in fixations, higher refixation probabilities, and less skipping in oral reading (Anderson & Swanson, 1937; Inhoff & Radach, 2014; Rayner, 2009). Research findings regarding regression rates in oral compared to silent reading are mixed. While some studies report higher regression rates in oral reading (Anderson & Swanson, 1937; Krieber et al., 2016) others report the reverse (Gregg & Inhoff, 2016), and yet others report similar regression rates (Huestegge, 2010; Kim et al., 2019). Vorstius et al. (2014) distinguished between intra-word and inter-word regressions showing that inter-word regressions are less common during oral reading.

Research also points to the increase of these reading modality differences as reading skill improves. Less skilled readers are more likely to have smaller differences between their eye movements in oral and silent reading than more skilled readers (Anderson & Swanson, 1937; Krieber et al., 2017). The modality by reading skill interaction could be because less skilled readers resort to an oral reading mode during silent reading (Anderson & Swanson, 1937). Theoretically, researchers have linked these differences to the size of the perceptual span differences.

1.2.2. Perceptual Span Differences between Oral and Silent Reading

Four studies provide evidence for smaller perceptual spans and limited parafoveal processing in oral compared to silent reading (Ashby et al., 2012; Inhoff & Radach, 2014; Pan et al., 2016; Pan et al., 2017). Using a gaze-contingent paradigm (McConkie & Rayner, 1975; Rayner et al., 2010), Ashby et al. (2012) were the first to examine differences in readers' use of parafoveal information by manipulating window size in the two reading modalities. Twenty-four undergraduates read 80 sentences: half aloud and the other half silently. The experimenters presented half of the trials in each reading modality condition with a one-word window (one word at fixation point) and the other half with a three-word window (one word at the fixation point and two words to the right). Their results showed a larger effect of window size for reading rate, fixation duration, and skipping probability in silent compared to oral reading. That is, readers were faster and skipped more words in the three-word window condition than in the one-word window condition in silent reading compared to oral reading. Interestingly, they found no effect of window size for the number of fixations in oral reading, while the effect was present in silent reading. Ashby et al. (2012) argued that their results might indicate parafoveal processing could operate either similarly or dissimilarly in the two reading

modalities. Differences in parafoveal processing could occur if working memory processes arising from articulatory needs deplete the attentional resources required to process words to the right. Alternatively, readers may be able to process words in the parafovea similarly, but interference from phonological representations of previously recognized words may mitigate the benefit obtained (Ashby et al., 2012).

Inhoff and Radach (2014) reported evidence for the latter possibility proposed by Ashby et al. (2012). That is, oral and silent reading share similar parafoveal processing mechanism, but there is a delay in the use of parafoveal information during oral reading. Again, using a gaze-contingent but boundary change paradigm (Rayner, 1975), 42 undergraduates read 64 sentences formatted in an alternating case. The researchers embedded a nonword preview mask within each sentence. After a no-delay (0ms) and delay conditions (50ms, 100ms, and 150ms) of viewing the pre-target word, a target word replaced the preview mask. Like Ashby et al. (2012), preview benefits were greater for silent compared to oral reading. Additionally, using survival analyses of gaze duration at the different delay conditions, Inhoff and Radach (2014) found that the survival curves between the 0 and 50ms delays were the same in oral reading but different in silent reading. That is, the use of preview information in the 0 and 50ms conditions were essentially the same for oral reading. Inhoff and Radach (2014) suggested this finding may be due to increased foveal load, which may have delayed the extraction of parafoveal information by 50ms in the no-delay condition. However, when comparing the no-delay condition to the 150ms condition, they found that the divergence point was much earlier in silent reading compared to oral reading. Their findings provided some evidence that the use of parafoveal information occurs much later in oral compared to silent reading.

The studies described above were conducted in English. Two studies have been conducted in Chinese, largely supporting the reduced parafoveal processing hypothesis. Pan et al. (2017) reported similar findings suggesting that reduced parafoveal benefit is potentially a language-universal phenomenon. Additionally, Pan et al. (2016) show that there may be a preference for early processing of phonological information in the parafovea during oral compared to silent reading. In their first experiment involving a single character manipulation of two simple Chinese characters to create semantic, phonological, unrelated and identical previews, no phonological preview benefits were obtained in oral reading. On the other hand, phonological preview benefits were obtained for later measures and semantic preview benefits for early and late measures during silent reading. However, in a second experiment, Pan and colleagues manipulated two compound characters in preview (word-level manipulation). This was important as

compound characters which are more representative of Chinese characters have phonological information embedded in the phonetic radical making phonological effects more likely to be observed. As predicted, the authors found early and late phonological preview benefits in oral reading, but only marginally significant effects for late measures in silent reading. These findings suggest a priority of phonological processing in the parafovea during the oral reading, at least for Chinese readers.

The studies described above generally agree that parafoveal information is not extracted at the same rate during oral and silent reading. The consequence of reduced preview benefits results in fixation durations that are longer for subsequent fixations and saccades that are shorter. However, more than these perceptual span differences, the coordination between the eye and the voice plays crucial role in the observed eye movement differences between oral and silent reading.

1.2.3. The Eye-voice Span in Oral Reading

Researchers have attributed oral-silent reading differences to the additional articulatory and coordinative demands of oral reading. Articulatory demands during word recognition can be likened to dual-task situations where processing in one task impacts processing in the second task. I will revisit this aspect of oral reading in Chapter 6. However, for the section, I will focus on the coordinative demands of oral reading.

Both processing streams of input and output require coordination and this coordination is largely measured using *the eye-voice span* (EVS). The EVS is the distance between the eye and voice during oral reading and is about two words in skilled readers (Rayner et al., 2012). Eye-voice span data can be collected using two major methods. The simpler way is by terminating text presentation at a predetermined position before participants finish reading. Termination of text presentation can be done by covering the rest of the text (occlusion; Quantz, 1897; Stuart-Hamilton & Rabbit, 1997) or turning off the lights (lights off; Cohn & Levin, 1967; Levin & Turner, 1966; Resnick, 1970). The number of words participants can recall is often taken as the EVS measure. The more technical and precise method involves simultaneous eye movement and voice recording (eye-tracking method). Interestingly, like the simpler methods, this sophisticated method has been used in several of the earliest research on the EVS. The eye-tracking method involves recording eye movements and voice at the same time. Eye-tracking equipment involved using either an apparatus that allowed photographic records of eye movements or electrooculography while voice output was recorded using a dictaphone, a pen or a tape recorder (see Levin & Addis, 1979 for more details on EVS equipments). Despite

the precision of simultaneous eye and voice recording, most researchers beyond 1960, used the more convenient EVS data collection method (i.e., lights-out method; Levin & Addis, 1979). However, with the advances in eye-tracking technology, recent research has used the eye-tracking method to measure the EVS.

Operationally, the EVS can be measured using either a spatial measure, i.e., the number of words or characters between the eye and the voice, or a temporal measure, i.e., the time between looking at and articulating a word. In the remainder of this section, I will give a background on the EVS and its modulation during reading, especially through eye movements. In later sections, I will review the differences in the EVS based on reading ability (section 1.3.5) and text characteristics (section 1.4.2). Except where otherwise stated, I use the spatial EVS in the rest of this section. In Chapter 5, I provide more details about the temporal measure.

Perhaps, no oral reading eye movement study is complete without the EVS. The earliest studies on eye movements incorporated this measure likely because oral reading was the dominant reading modality (Buswell, 1920; Fairbanks, 1937; Quantz, 1897). However, as the focus shifted to skilled silent reading, the EVS was largely forgotten until the last decade or so (De Luca et al., 2013; Inhoff et al., 2011; Laubrock & Kliegl, 2015; Silva et al., 2016; Zhou et al., 2021). The first description of the EVS was by Quantz (1879) where they examined factors influencing the EVS. Quantz (1897) reported that the EVS varied along the line with about 7.4 words at the start and 3.8 words at the end. Importantly, he found that silent reading rates correlated positively with the width of the EVS. About 40 years later, Buswell (1920) conducted a thorough and systematic investigation of the EVS. Buswell (1920) argued that a reasonable EVS is necessary for two purposes. First, to ensure that readers can extract the meaning of the text. Second, to ensure that readers have a sufficient visual sample of text to inform pronunciation of words. For example, consider the sentence, "*After a minute but rapid examination of their weapons, they ran down the valley*" (Buswell, 1920, p. 89). Having a span while reading this sentence aloud is necessary to pronounce and understand the word "*minute*" as the adjective meaning *very small* rather than as the noun, meaning *a period of time*.

The EVS combines measurements from two domains i.e., the oculomotor system and the speech system both linked by the central cognitive processing system. Because of this, it is important to consider what the EVS tells us precisely about the reading process. At the word level, the EVS can be construed as a measure of lexical processing efficiency i.e., how well readers are able to recognize and assimilate words (Fairbanks, 1937). At the sentence level, it can be taken as a measure of language processing where

a reader's ability to integrate multiple words to make meaning is captured by how far the eye are in advance of the voice. This proposition is consistent with Levin and Wanat (1967) who found that the EVS was sensitive to differences in the surface and deep structures of sentences. Sentences where the surface structure was different from the deep structure (e.g., *His brother was beaten up by the park*) had shorter EVSs than sentences with the same surface and deep structure (e.g., *His brother was beaten up by the gang*).

More broadly, the EVS is not just associated with lexical and language-related processes but also domain-general cognitive processes like working memory. The EVS is associated with the amount of phonological information that needs to be continuously buffered in working memory before articulation begins (Gordon & Hoedemaker, 2016; Laubrock & Kliegl, 2015). This working memory link was further confirmed when Laubrock and Kliegl (2015) found that fixation durations regulated the EVS of low frequency and less predictable words more than high frequency and more predictable words. They argue that the oculomotor system is constrained by working memory capacity. Therefore, more capacity would be reflected in a larger span and forward movements of the eyes and vice versa. In summary, studying the EVS gives us a rich understanding of the reading process, aiding our understanding of lower-level processes and higher-order cognitive processes during reading.

1.2.4. Modulation of the Eye-voice span

According to Buswell (1920), the EVS is elastic and varies depending on the cognitive demands required by the text. For example, difficult words may lessen the span. This elasticity may require that the EVS be kept within a manageable limit to prevent an overload of working memory capacity. Buswell (1920) was the first to associate oculomotor mechanisms with EVS modulation. To clarify this relationship, he measured the EVS for the 10 longest (21.2 character spaces) and shortest fixations (19.6 character spaces)) expecting that the EVS should be significantly larger for the longest fixations and shorter for the shortest fixations. However, the data did not support the proposition of increasing fixation durations to reduce the EVS. Only a difference of 1.6-character spaces was observed between the two categories of fixations. This result led to the conclusion that large spans are reduced by a series of short fixations as much as long fixations (Buswell, 1920). About 90 years later, Inhoff et al. (2011) found that the temporal EVS was adjusted by longer first fixation, gaze duration, and regressions in 29 English university undergraduates. Additionally, the length of the outgoing saccade aided the reduction of the EVS. Laubrock and Kliegl (2015) replicated these findings in

German, showing that the spatial EVS during oral reading is a better predictor of single fixation durations than word-level variables such as frequency and length. Notwithstanding, these landmark findings, less is known about how modulation of the EVS occurs in children. Additionally, the involvement of the voice in modulating the span is empirically vague. However, three researchers provide some hints. According to Buswell (1920), "The eye is the controlling factor rather than the voice, and other factors of perception must operate to lengthen eye pauses" (p.81). Laubrock and Kliegl (2015) in agreement with Buswell (1920) propose that "Given that the voice proceeds fairly linearly through the text, most of the adjustment is actually performed by the oculomotor system" (p. 17). In contrast, Fairbanks (1937) describes the elasticity and modulation of the EVS by stating, "The eye-voice lead may be increased by forward movement of the eyes or by lagging of the voice; it is decreased by the reverse type of inter-action" (p.85).

Therefore, unravelling the impact of the EVS on speech production is a mystery that an oral reading eye-tracking paradigm can resolve.

1.3. Eye Movements and Reading Ability

In recent years, the ease with which reading researchers can collect eye movement recordings has led to several publications involving a wider range of participants, including developing and atypical readers. These have increased our understanding of oculomotor, lexical, and semantic factors involved in reading development and reading difficulties. This section explores the basic and perceptual span differences between eye movements in children and adults. It also explores individual differences in eye movement behaviour and the EVS.

1.3.1. Basic Differences and Similarities between Eye Movements in Children and Adults

Generally, it is well accepted that as children become older, fixation durations, refixations, and regressions decrease while there is an increase in saccade length and word skipping (Aghababian & Nazir, 2000; Blythe, 2014; Blythe et al., 2011; Blythe et al., 2009; Buswell, 1920; Huestegge et al., 2009; Johnson et al., 2018; Joseph et al., 2009; Rayner, 1986; Vorstius et al., 2014). For example, children in grade two (7 years) and adults have an average fixation of 290ms and 250ms respectively and saccade length of 4-character spaces and 8 character spaces respectively (see Blythe & Joseph, 2011; Rayner, 1986; Vorstius et al., 2014 for a developmental overview of eye movement behaviour). These patterns of eye movements become adult-like at about 11 years (Blythe

& Joseph, 2011) and suggest that the most meaningful investigation of developmental changes in eye movements during the reading process should involve participants that are less than this age.

Despite the differences in eye movement patterns between children and adults, there are some similarities in their reading processes. Children's initial landing positions in words are similar to adults (Aghababian & Nazir, 2000; Joseph et al., 2009; Zang et al., 2013). For example, Aghababian and Nazir (2000) examined developmental differences in children's ability to recognize words correctly at different viewing positions and found no significant differences between all five grades (6-10 years). In another study, Joseph et al. (2009) found similar initial landing positions for four, six, and eight-letter words in children aged 7 to 10 years and adults. This suggests that saccade length differences between children and adults are primarily due to adults' tendency to skip words more and children's tendency to refixate long words, rather than a difference in initial landing position (Joseph et al., 2009). That age does not necessarily impact inter-word saccade targeting may suggest that the saccadic targeting system is not greatly influenced by linguistic proficiency but may be strictly under oculomotor control (Blythe & Joseph, 2011). This assumption is consistent with the finding that linguistic properties of words such as frequency and predictability do not influence initial landing positions. Another similarity between children's and adults' eye movement is their rate of visual processing. Similar visual processing rates between children and adults was demonstrated in two experiments that showed word frequency effects across three groups (7–9-year-olds, 10–11-year-olds, and adults) for very short visual presentation of target words (40ms). These two key similarities of visual processing and inter word saccade targeting suggest that linguistic proficiency and print exposure are likely candidates for the slower rates of reading in children rather than underdeveloped visual processing and oculomotor planning skills (Blythe, 2014; Blythe & Joseph, 2011; Blythe et al., 2009; Leinenger et al., 2017).

1.3.2. Perceptual Span Differences in Children and Adults

The observed differences in the eye movement patterns between children and adults have been associated with differences in their perceptual span (Rayner, 1983). The use of gaze-contingent display paradigms with children has permitted the investigation into the limits of information extraction compared with adults (Rayner, 1975). Although children have asymmetrical perceptual spans as early as seven years of age, adults typically have a slightly wider perceptual span than children (Blythe & Joseph, 2011; Rayner, 1986), This

has been attributed to the difficulties children face with language processing. Specifically, when the window size is measured as the number of characters or number of words, second graders have a perceptual span that extends 11 characters or 2 words to the right of fixation compared to adults with a perceptual span extending 14 characters or 3 words to the right (Rayner, 1986). In the same vein, Häikiö et al. (2009) showed a developmental increase in the letter identity span with 8-, 10- and 12-year-olds identifying 5, 7, and 9 characters to the right of fixation, respectively. However, before second grade, Sperlich et al. (2015) reported no difference in the perceptual span of grades one and two German readers indicating that some basic amount of reading instruction is required to take advantage of parafoveal information.

1.3.3. Parafoveal Preview Benefits in Children

In line with evidence on the perceptual span reviewed above (Häikiö et al., 2009; Rayner, 1986), older children benefit more from parafoveal previews of upcoming words than younger children (6-12 year olds; Johnson et al., 2018) during silent reading. However, the picture may appear different or inconclusive during oral reading. Marx et al. (2015) reported that German fourth and sixth graders showed comparable preview benefits during oral reading. Marx et al. (2015) argued that diminished parafoveal processing in oral reading compared to silent reading may have influenced the sixth graders' preview benefit. However, they also noted that other explanations are more likely since the fourth graders exhibited an adult-like preview benefit. First, the possibility that the parafoveal pre-processing benefit does not require the use of the entire length of the perceptual span but that even the first few letters may be sufficient to constrain a word's identity (Ashby & Rayner, 2004; Marx et al., 2015). Second, the transparency of grapheme-phoneme correspondences in an orthographically regular language like German could cause both groups of readers to use similar serial decoding that eliminates any preview advantage the sixth graders had over the fourth graders. This pattern may thus lead to similar preview benefits between the two groups. Marx et al. (2016) further investigated developmental changes in preview benefit by including a group of second graders. They found that preview benefit was absent for second graders and present for fourth and sixth graders in measures of single fixation and gaze duration data. The preview effect was similar across all grades for first fixation data. They note that the single fixation finding should be interpreted with caution as very few target words received single fixations (Marx et al., 2016). However, no comment was given concerning gaze duration. Nevertheless, a useful contribution from this study is that reading rate, which overlapped between the grades,

significantly predicted preview benefits. Additionally, nonword decoding predicted preview benefits better than reading experience as measured by grade level.

Other studies distinguish between the nature of information extracted between adults and children. German children aged 8 years seem to extract phonological information in the parafovea compared to adults who can use orthographic information (Tiffin-Richards & Schroeder, 2015a). However, the extraction of orthographic information in English appears to be similar for children aged 8 to 9 years, and adults (Milledge et al., 2021; Pagan et al., 2016). In these studies, the substitution of external letters was harmful to both groups compared to internal letter substitution (Milledge et al., 2021) and both groups benefitted more from transposed letters compared to substituted letters in the parafovea equally (Pagan et al., 2016). These similarities between children and adult parafoveal pre-processing are consistent with more recent studies showing that first letter bias in parafoveal processing is orthographically driven and phonological information is extracted similarly in both groups (Milledge, Liversedge, et al., 2022; Milledge, Zang, et al., 2022)

To sum it up, children can take advantage of parafoveal previews during oral and silent reading. While the study by Marx et al. (2016) revealed grade differences in gaze duration, it seems clear that the more important determiner of preview benefit is reading skill. In the next section, I zoom in on individual differences in eye movement measures.

1.3.4. Individual Differences in Eye Movements

Reading skill has often been indexed by grade or age in eye movement studies (Häikiö et al., 2010; Häikiö et al., 2009; Rayner, 1986), or by comparing groups of readers such as children compared with adults or clinical populations (i.e., people with dyslexics). Yet a promising area in the field is individual differences (Kuperman & Van Dyke, 2011; Lee et al., 2021; Marx et al., 2016; Veldre & Andrews, 2014, 2015). Individual differences reading research is important to understand what skills are necessary for reading acquisition and importantly, identify and support readers with reading difficulties (Long & Freed, 2021). Blythe and Joseph (2011) highlighted the need for a distinction between the influence of age and reading skill especially during reading development. Since then, a growing body of work has revealed that reading skill impacts the eye movements of skilled and developing readers.

Researchers interested in individual differences have used several measures to examine differences in skilled readers' eye movements. These include word and non-word reading, naming, spelling, comprehension, working memory, etc. (see Kuperman &

Van Dyke, 2011 Appendix A for a non-exhaustive list). Interestingly, Kuperman and Van Dyke (2011) found that amongst the 18 skills assessed, only word identification and rapid automatized naming (RAN) speed significantly and reliably impacted early and late temporal and spatial eye movement measures. Therefore, in this thesis and section, I will limit the review to RAN speed and word reading efficiency but also include spelling and vocabulary, which are considered indexes of lexical quality as will be seen briefly in this section and section 1.5.2.

The relationship between RAN and reading has long been established (Bowers, 1995; Clarke, Hulme & Snowling, 2005; Wolf & Bowers, 1999). However, the underlying reason for this relationship is contentious with orthographic, phonological, domain-general cognitive, and serial-oculomotor processing accounts (Georgiou et al., 2013; Georgiou et al., 2016; Kuperman & Van Dyke, 2011; Papadopoulos et al., 2016). RAN is considered a microcosm of reading as the ability to quickly name familiar symbols, objects, numbers or letters is similar to what reading texts involves (Norton & Wolf, 2012). The phonology of each item in the RAN task needs to be retrieved and speech output generated rapidly. Similar to the RAN task, decoding words by computing phonology from orthographic representations is a key skill for fluent reading and comprehension (Gough & Tunmer, 1986). The ability to decode carries over to eye movement records in fast and automatic lexical access as revealed by short fixation durations. Yet while word decoding is important, spelling skill has received recent attention as a valid measure of lexical quality separate from word reading and comprehension (Perfetti, 1992; Veldre & Andrews, 2014). Word decoding involves translation from orthography to phonology and can rely on partial orthographic cues whereas spelling involves translation from phonology to orthography and requires precision in orthographic representations (Frith, 1980; Perfetti, 2007; Veldre & Andrews, 2014). In skilled reading, there has been a dissociation between reading and spelling skills (Parker & Slattery, 2021; Slattery & Yates, 2018; Yates & Slattery, 2019), where spelling ability is associated with saccade targeting and reading ability is associated with fixation duration measures. However, the extent to which this dissociation occurs in developing readers is unknown. One study examined spelling in relation to eye movements. In a longitudinal study, Ashby et al. (2013) examined eye movements during a receptive spelling ability task in grade two and its relationship with grade three oral and silent reading fluency. While they found no longitudinal relationship between these measures and attributed this to a small sample, they did find that fixation time spent on selecting

the correct spelling of low frequency words correlated with silent and oral reading fluency in grade two.

Finally, semantic knowledge as measured by vocabulary knowledge is mostly used as a paired subcomponent of reading ability with reading comprehension (Connor et al., 2015; Veldre & Andrews, 2014). Vocabulary knowledge relates to knowledge of and access to word meanings (Braze et al., 2016) which comes to bear during reading, speaking, writing and listening situations. During skilled reading, research shows that vocabulary impacts skipping (Kuperman et al., 2018) and initial landing position in words (Kuperman & Van Dyke, 2011). Like adults, children's word and non-word reading impact temporal eye movements (e.g., gaze duration, de Leeuw et al., 2016; Foster et al., 2018; Hessel et al., 2020; Lee et al., 2021). However, the evidence of an impact of vocabulary knowledge on eye movement behaviour in developing readers is inconsistent (see Hessel et al., 2020; Lee et al., 2021). Lee et al. (2021) found that vocabulary did not predict any eye movement measure while controlling for other reading skills such as word reading and comprehension while Hessel et al. (2020) found that vocabulary predicted gaze durations.

The above review points to some unknowns in eye movement developmental reading research. There is ample room to examine the influence of individual difference measures on children's eye movements. The following section discusses documented sources of individual differences in the EVS.

1.3.5. The Eye-voice Span: Group and Individual Differences

The EVS is approximately 15-character spaces in skilled English readers (Buswell, 1920) and 16-characters in skilled German readers (Laubrock & Kliegl, 2015). Thus, the eyes mostly lead the voice by an average of two to three words (Inhoff et al., 2011; Rayner, 2012). This estimate is smaller for younger and less skilled readers (see Table 1.1). Like eye movement measures, individual difference variables such as reading ability, grade level and age influence the EVS (Buswell, 1920; De Luca et al., 2013).

Historically, reading comprehension tests have been used as the measure of reading ability in relation to the EVS. For example, Buswell (1920) found the EVS was smaller for poor readers than good readers across different grade levels. Reading ability was measured for the primary grades using the Gray's Oral Reading Paragraphs while the other grades and adults were subjectively classified as good or poor readers. Regardless of the sample selection method used by Buswell, his finding is consistent with Fairbanks (1937) who used the Iowa Silent Reading Test to discriminate between good and poor

readers. Further support for reading ability comes from Buswell's (1920) grade analysis of the EVS where an inconsistent increase in spatial EVS was reported. When other grade comparisons showed the expected increase in the EVS, fourth graders had smaller EVSs compared to third graders and sixth graders had smaller EVSs compared to fifth graders. This pattern is equally consistent with findings that eighth-grade participants showed larger EVS than participants in tenth grade (Levin & Turner, 1966). Although in the study by Levin and Turner (1966), participants were volunteers and were not selected based on an assessment of reading ability. Such inconsistencies are likely driven by reading ability differences between selected students of different grades. While Buswell (1920) used a comprehension test to discriminate good and poor readers within grades, the ability of readers across grades were not compared.

Some other researchers argue that grade may be more important than reading ability. Holgerson (1977) reported that no EVS differences between good and poor readers in fourth and fifth grades. Reading ability was assessed with comprehension scores on Gates-MacGinitie Reading tests. However, the poor fourth and fifth grade readers had a significantly larger EVS compared to average third graders in the study. Holgerson (1977) proposed that the EVS was not related to reading ability but a function of grade or age reflecting increased experience with oral language and anticipating speech patterns. An earlier study by Resnik (1970) casts doubts on this assertion with EVS of third and fifth graders having similar EVS. Although, both grades differed significantly from college-age students. Inconsistencies in these EVS findings across grades may not only be due to reading ability differences (e.g. Buswell, 1920), but may also reflect the limitations of the light out apparatus and methodology used. The lights-out approach differs from using eye-tracking in measuring the EVS in several ways. First, any measurement that does not include the position of the eyes would likely be inaccurate and only an estimation. Second, inaccuracies in this estimation could also arise from differences in the lights-off timing as this was usually done manually by the experimenter. Third, participant's memory abilities, guessing or looking ahead behaviour may influence this estimate. Laubrock & Kliegl (2015) also provide an interesting differentiation noting that because reading ends when using the lights-off paradigm, the EVS is likely to be overestimated as no new information from the eyes is coming in. Whereas, readers are continually presented with text during eye tracking which causes greater constraints on how much information can be buffered. Consequently, while the EVS using the lights-off paradigm provides some useful indication of the EVS, it is in the strict sense of the

measure not an accurate reflection. Therefore, lights-off studies showing inconsistent grade effects or otherwise, on the EVS, cannot be relied upon.

Overall, it appears that while grade may have an influence on the EVS, reading ability is also a strong factor. Using modern day eye-tracking equipment can disentangled these factors. Older children and participants with better comprehension scores are likely to have a larger EVS than younger children and those with poor scores. Little is, however, known about how reading-related skills such as decoding may be related to the EVS. Using eye-tracking equipment, a recent study showed that 11-year-old readers with dyslexia show a smaller EVS than age-matched controls (De Luca et al., 2013). With evidence that dyslexic readers have a primary deficit in decoding visual (Ziegler et al., 2003), this clearly support a close relationship between decoding ability and the EVS beyond grade or age effects.

Table 1.1. Developmental changes in the eye-voice span.

Author	**Method (unit)**	**Grade**										
		2	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**Adults**
Buswell (1920)	Eye-tracking (character spaces)	8.2	11.8	10	13.2	11.6	12.6	-	13.6	13.5	11.4	14	15
Levin and Turner (1966)	Lights-off (words)	3.2		4.4		2.3		4.2		4.0			5.0
Cohn and Levin (1967)	Lights-off (words)	3.0		4.3					4.0		4.6		
Resnick (1970)	Lights-off (words)		2.8		3.2								4.6
Holgerson (1977)	Lights-off (words)												
De Luca et al. (2013)*	Eye-tracking (characters)					13.8							
Laubrock & Kliegl (2015)+	Eye-tracking (characters)												16

Note. * Data from Italian readers. Same-age readers with dyslexia had an EVS of 7.9 +Data from German readers

1.4. Eye Movements and Text Characteristics

So far, I have examined reading modality and ability influences on eye movement behaviour. However, another critical variable that has received the most attention is text

characteristics. Text factors that may influence eye movement behaviour include visual, linguistic (word or sentence level) and typographic factors (Kuperman et al., 2018; Rayner, 1998; Rayner, 2009). Saccade targeting is usually based on visual factors such as word length, parafoveal word length, word spatial extent and inter-word space cues (Hautala et al., 2011; Hautala & Loberg, 2015; Rayner, 1979; Rayner, 2009; White et al., 2005). For example, saccades are usually targeted towards more central locations in longer words than short words to aid lexical processing (Joseph et al., 2009; McConkie et al., 1988; Rayner, 1979). However, in addition to these visual factors, linguistic properties such as word frequency and predictability of a word in context determine fixation durations. For example, gaze durations are shorter for short words as they have fewer letters to be processed (Hautala et al., 2011; Juhasz, 2008; Kliegl et al., 2004; Pollatsek et al., 2006). In the same way, words that are high frequency, which are more familiar to the reader, receive shorter fixations than low frequency words (Henderson & Ferreira, 1990; Raney & Rayner, 1995; Rayner, 1998; Rayner, Reichle, et al., 2006; Reingold et al., 2010; Staub et al., 2010). These length and frequency effects on eye movement measures mirror findings from naming and lexical decision (Juphard et al., 2006; Morrison & Ellis, 1995; New et al., 2006; Schilling et al., 1998). Furthermore, highly predictable words from context receive shorter fixations than unpredictable words due to pre-activation of possible words that aid subsequent identification (Kliegl et al., 2004; see Staub, 2015 for a review).

Children, even more than adults, are affected by these word characteristics. For instance, the effects of word length, word frequency, and word predictability are modulated by reading skills (Blythe et al., 2011; Blythe et al., 2009; Huestegge et al., 2009; Hyona & Olson, 1995; Johnson et al., 2018; Joseph et al., 2009). These studies agree that developing readers take more time to process long compared to short words and low compared to high frequency words and that this effect decreases as reading skill develops. Some researchers interpret length effects in children as resulting from serial letter processing (Barton et al., 2014; Tiffin-Richards & Schroeder, 2015b). As reading experience increases, a shift from serial letter-by-letter decoding to whole word recognition occurs (Ans et al., 1998; Coltheart, 2006). However, an intermediate level between letter-by-letter processing and whole word processing is likely a syllable processing level (Ehri, 2005b, 2017; Häikiö et al., 2016). While this has received enormous attention in behavioural studies, few studies have examined it using eye movement records.

The focus of this thesis is on oral reading and because syllables encode information about pronunciation such as stress, length, pitch, rhythm and intonation (Hasenäcker & Schroeder, 2016), it was considered a critical variable in relation to understanding underlying reading processes in children. Compared to phonemes which are smaller phonological units, syllables are considered the smallest unit of speech production and planning which occur in isolation (Cholin et al., 2011; Norris & Cutler, 1988). Additionally, compared to morphemes which are the smallest units of meaning, syllables retain a strong connection to oral reading fluency compared to reading comprehension (Nunes et al., 2012). Therefore, an oral reading modality provides an excellent opportunity to examine how readers use syllabic information during lexical processing. In the next section, I will review syllable units in word recognition across different tasks and languages.

1.4.1. Syllable Units during Word Recognition

Syllables are units of speech comprising of a sequence of phonemes and an internal structure of an optional onset (consonant or consonant cluster), nucleus (vowel) and an optional coda (consonant or consonant cluster; Trieman, 1983). Syllables can also be organized into onset and rime where the rime comprises of the nucleus and the coda (Treiman, 1989). Although, syllables are involved in speech production and perception, evidence from skilled readers reveal that they are equally functional psychological units in word recognition (Alvarez et al., 2001; Conrad et al., 2009; Stenneken et al., 2007). In addition to the behavioural methods employed by the afore-cited studies, on-line methods such as eye tracking and event-related potential (ERP) experiments have been used to investigate syllable processing primarily in adult readers (Ashby, 2010; Ashby & Clifton,, 2005; Drieghe et al., 2019; Pelczarski et al. 2019).

In contrast, syllable processing has been limited to mostly behavioural methods in developing readers (see Gagl, 2010 for an exception). For example, hyphenation within syllables disrupts reading more than hyphenation at syllable boundaries for Finish first and second graders (Häikiö, Bertram, et al., 2015; Häikiö et al., 2018) suggesting the importance of syllables as units in word recognition. Additionally, syllable compatibility effects (faster detection of whether a target syllable e.g., *BA*, was present at the beginning of a target word with either the same (*BA.LLON)* or different (*BAL.CON)* initial syllable) were present in good French first grade readers (6 years) but not in skilled readers reading high frequency words (Colé et al., 1999). This finding is consistent with what has been found in Spanish using a similar paradigm (Jimenez et al., 2010) and shows that children

are sensitive to syllables as processing units after a year of reading instruction. However, this pattern may change as reading experience accumulates. The nature of changes in the role of syllables within school-age years is less clear and inconclusive.

Alvarez et al. (2016) found that second graders (7 years) and sixth graders (11 years) were no different in their ability to spot one-syllable words (ending at a syllable boundary) at the beginning of nonwords compared to words that did not end at a syllable boundary. This picture seems at odds with a developmental progression in using letters in word recognition. Similarly, in a lexical decision experiment, Hasenäcker and Schroeder (2016) found no reaction time differences between second grade (7 years) and fourth grade (9 years) German readers in conditions where disruptions were located at syllable congruent and incongruent positions. Although second graders seemed to prefer syllables and fourth graders morphemes as processing units (Hasenäcker & Schroeder, 2016). In contrast, another German study by Gagl et al. (2010) showed diminishing number of syllable (one vs. two) effects between grades two and four. Beyond grade level, Hautala et al. (2012) examined the role of word length in letters and syllables in typical and dysfluent Finnish second-grade readers with an average age of 8 years. Specifically, these researchers manipulated syllable number using six-letter words and nonwords of either two or three syllables. They found that typical readers did not show syllable number effects in lexical decision and naming latency. However, more syllables took less time in naming response duration for words for these readers. On the other hand, for poor readers showed more syllables took more time in lexical decision (words and nonwords) and in naming latency of nonwords (Hautala et al., 2012). However, they found no effect of syllables for response duration for poor readers.

In another French study, Bijeljac-babic et al. (2004) reported that the effect of general length (letter, phonemes, and syllable combined) decreased with age for naming and an online identification task (Reya et al., 1998). Furthermore, while the effects of phonological length (phoneme and syllable) did not interact with age for naming latency, there was an interaction for naming errors for third graders (8.5 years). This interaction indicated that third graders made more errors on words with more syllables and phonemes than words with fewer syllables and phonemes compared to fifth graders (10.5 years) and adults. More importantly, further regression analysis separating the effects of phonemes and syllables indicated that number of syllables explained more variance in the third graders' naming latency and reaction times on the online identification task compared to the other groups. (Bijeljac-Babic et al., 2004). It may be difficult to disentangle syllable number effects due to the variability in the stimuli. However, that number of that syllables

were most predictive of third graders naming latency suggests that these readers show a preference for syllable size units. Whether or not a change occurs in the sensitivity to syllable units with increasing age, is still an open question. Two English studies have investagated syllable number effects. Juel and Holmes (1981) embedded one and two syllable words in sentence frames and required second and fifth grade children to read aloud or silently. They found that sentences with one syllable words were faster to read compared to sentences with two syllable words. However, word length was confounded with syllable number: two syllable words had more letters than one syllable words. Interestingly, this effect was more pronounced in oral compared to silent reading and good readers showed smaller effects of syllable number compared to poor readers in both grades two and five (No comparsion was made between the two grades). In another study, Duncan and Seymour (2003) investigated the syllable number effect in 11-year-old participants. They reported that an increase in syllable number led to an increase in error rates for non-words but not for words.

What is clear from these studies is that syllables are functional units in word recognition across languages in developing readers. In line with the psycholinguistic grain size theory (Ziegler & Goswami, 2005), language orthographic depth may mediate some of these findings. More transparent orthragraphies such as Spanish and German may show stable syllable effects across grades due to their reliance on smaller grain sizes (e.g., syllables in this case) compared to whole words (although see Gagl et al., 2010 for contrasting evidence in German). On the other hand, less transparent orthographies like French and English may show differences across grade due to their reliance on larger grain sizes (e.g., whole words) as reading experience accummulates. However, this proposition may be difficult to explain as reading skill or grade modulate syllable processing in Finnish (Hautala et al., 2012) and German (Gagl et al., 2010). One commonality here is the experimental paradigm utilized by these studies as well as the French and English studies where number of syllables is manipulated. Therefore, using an on-line eye tracking paradigm where manipulated target words are embedded in sentence contexts offers a natural and unobstrusive method of assessing the role of syllables and whether findings from word recognition paradigms generalise to everyday reading.

1.4.2. The Eye-voice span and Text Characteristics

The elasticity of the EVS is influenced by various factors. While some early researchers have probed into physical text characteristics such as spacing and position in line, others

have examined how linguistic characteristics impact the EVS. For example, Hochberg et al. (1966) found that the EVS was smaller when inter-word spaces were filled indicating that such presentation impacted readers' ability to parafoveally process words and rely on foveal processing. Similarly, college students viewing text on an inverted screen have smaller EVS than controls (Resnick, 1970).

Quantz (1879) and Buswell (1920) studied the influence of word position on a line with conflicting results. While Quantz (1897) reported a significant difference between the beginning and middle of lines, Buswell (1920) reported no differences between these regions. However, these researchers agree that the EVS is narrower at the end of a line than at the beginning. Parallel to position in a line, the EVS at the end of a sentence is narrower than at the start (Buswell, 1920; Fairbanks, 1937; Quantz, 1897). According to Buswell (1920), the EVS varies significantly according to position in a sentence and not necessarily position in a line. This finding reveals the value of the EVS in meaning recognition and top-down processes rather than bottom-up processes as described in section 1.2.3. Buswell (1920) concluded that meaning units rather than line units determine the EVS. That is, readers move their eyes so that they can understand the text and read with appropriate intonation.

Although very little research exists, word frequency and length effects on the EVS have been reported. High frequency words facilitate a larger EVS, compared to low frequency words (Buswell, 1920; Halm et al., 2011; Laubrock & Kliegl, 2015). The EVS is also smaller for longer words than shorter words (Halm et al., 2011). These word frequency and length effects suggest that ease of processing is synonymous with a wider EVS. However, the extent to which the EVS captures syllable number effects remains unexplored. Because syllables are representational units in speech production (Levelt et al., 1999), it is plausible that information represented in working memory as measured by the EVS is stored as syllable units during oral reading.

1.5. Theoretical Framework

In this section, I examine models of eye movements during reading, word recognition and reading development models which will form a framework for aligning the research questions outlined in this thesis. Specifically, the E-Z reader and SWIFT models are reviewed as potential models for understanding eye movements during oral reading. The lexical quality hypothesis is examined to guide the exploration of individual differences in eye movement behaviour and the EVS. Additionally, Ehri's reading development

model and two models of multisyllabic word reading are examined in line with our investigation of syllable processing during development.

1.5.1. Models of Eye movement during Reading

E-Z Reader Model

E-Z reader is a cognitive control model of eye movements suggesting a tight link between the mind and the eye (Reichle et al., 2012), unlike oculomotor control theories (Yang & McConkie, 2001). There are two core assumptions of this model: (*i*) word identification occurs in two stages with the first stage signalling an eye movement, and (*ii*) attention is allocated from one word to another in a serial fashion. Therefore, based on the second assumption, the E-Z reader model is commonly termed a serial attention shift (SAS) model (Reichle et al., 2013; Reichle et al., 2003). During the first stage of lexical access (L1), called the *familiarity check*, a word's orthographic representation is activated and is sufficient to trigger the programming of a saccade to the next word. The activation of phonological and semantic representations occurs in the second stage (L2) where full word identification triggers an attentional shift to the next word. The attentional shift to the next word begins its familiarity check stage. The time taken to complete L1 is dependent on the word's frequency and predictability. These same variables account for the completion time in L2, however, predictability influences the L2 stage more than L1 as highly predictable words incur no cost in the L2 stage (Reichle et al., 2003).

A fundamental feature of this model is the dissociation between saccade programming and attention shifting which accounts for foveal load effects and reduced preview benefits (Henderson & Ferreira, 1990). Saccade programming occurs in two stages. First, an early labile stage (M1) of saccade programming that is susceptible to cancellation and involves calculating the distance between current fixation and saccade target. Second, a late non-labile stage which is not subject to cancellation and involves sending the command to execute and executing the saccade by the motor system. What is important about these saccade programming stages is that they both occur within a constant time after L1 is completed. Therefore, because the time to shift attention is variable and dependent on a word's frequency, high frequency words will have more time between completion of L2 and M2. Conversely, low frequency words will have less time between the completion L2 and M2. The time intervening between L2 and end of M2 is the time allocated for parafoveal processing of the next word (see Figure 4 in Reichle et al., 2003). Hence, high frequency words would allow more time for parafoveal processing than low frequency words. However, E-Z reader model is a silent reading model, and it

is unclear how it can successfully account for the dynamics of the EVS and oral reading more generally. I will return to this later in the General discussion section.

SWIFT Model

The SWIFT (Saccade-generation with Inhibition by Foveal Targets) model of eye movements during reading is a computational model that assumes a unifying mechanism for all eye movements such as forward saccades, regressions and refixation (Engbert, et al., 2002; Engbert et al., 2005; Seeling et al., 2020). This model in contrast to the E-Z reader proposes that words are processed in parallel. Subscribing to a spatially distributed lexical processing mechanism, at a given fixation, multiple words in the perceptual span are being processed, albeit with different levels of activations and attention allocation (Kliegl & Engbert, 2003). In English language and other alphabetical scripts, there is greater activation to the right of the fixation which is the direction of attention during reading (Laubrock et al., 2006). Evidence for parallel word processing comes from studies showing that frequency, predictability and length of adjacent words to the currently fixated word impacts fixation durations of the current word (Kliegl et al., 2006; Kliegl, 2007). Another key feature of this model that distinguishes it from the E-Z reader model is that eye movements are primarily determined by an automated random timer which could be inhibited by lexical processing of the foveal word. Therefore, lexical processing seems to be a secondary force behind saccade latency or fixation durations. That is, the difficulty of a target word could delay the execution of a saccade programmed by the random timer.

Notwithstanding these differences, the SWIFT and E-Z reader model share some similarities in that two stages are involved in lexical processing and saccade programming for both models. Words outside the perceptual span have a lexical activation of zero. As soon as words enter the field of effective vision (perceptual span), their lexical activation increases from zero to a maximum activation threshold which is determined by the word's frequency. This first stage is called the lexical pre-processing stage. However, because word predictability is independent of visual input and dependent on prior sentence context (Engbert et al., 2005; Laubrock et al., 2006), predictability impacts processing rate and not lexical activation. In addition, each word's processing rate is further dependent on the fixation location where words closet to the fixation have higher rates than words farther away. As the word reaches the point of complete processing, lexical activation declines from the maximum to zero. This second stage is called lexical completion.

With regard to saccade programming, this occurs in labile and non-labile stages. Saccades can be cancelled whilst in the labile stage if a new saccade programme is generated. However, if this is not the case, the selection of target word based on the greatest lexical activation occurs and saccade programming reaches the non-labile stage which cannot be cancelled (Laubrock et al., 2006). Like the E-Z reader model, the SWIFT model has been used to model eye movements during silent reading tasks and less is known about how articulatory demands can influence model parameters. However, Laubrock and Kliegl (2015) present evidence that there are no reading modality differences in how lexical properties of adjacent words to the currently fixated influences its fixation duration. Thus suggesting that a distributed processing model like the SWIFT can explain oral reading behaviour. In the General discussion, I return to how SWIFT model could potentially account for eye movement patterns during oral reading.

1.5.2. Lexical Quality Hypothesis

According to linguistic control eye movement models, the key difference between a developing reader and a skilled reader is the rate of lexical processing (Mancheva et al., 2015; Reichle et al., 2013; Reichle et al., 2009). While word characteristics influence the decision to move the eyes, reader characteristics can also influence eye movements. The lexical quality hypothesis supports this idea and proposes that the quality of lexical representations accounts for individual differences in reading. The three components of word recognition (orthography, phonology, and semantics) are embedded in this model**.** Well-specified orthography, redundant phonology, and flexible semantics characterise high-quality representations and allow rapid, coherent, and context-free word identification (Perfetti, 2007; Perfetti, 1992; Perfetti & Hart, 2002). Well-specified orthography connotes precise knowledge of the letter sequences that make up words (Veldre & Andrews, 2014). Furthermore, redundant phonology implies that the orthographic to phonology mappings are multi-layered and each layer could be used flexibly to achieve word recognition (Booth et al., 1999). The meaning of words also needs to be flexibly represented because different word forms (orthography) could have the same meaning dependent on context (Perfetti, 2007). One key feature of this hypothesis is that all three components need to be connected tightly such that the sight of a word yields fast activation and retrieval of each component at the same time (Perfetti & Hart, 2002). According to Perfetti and Hart (2002), lexical quality is measured by examining spelling, pronunciation, and meaning identification. Therefore, one of the

crucial aims of this work, is to examine how individual differences in lexical quality accounts for the variation in eye movements and the eye-voice span.

1.5.3. Ehri's Model of Reading Development

As stated at the beginning of this introduction, learning to read involves mapping sounds and symbols of language (Ehri, 2005a, 2005b). This idea is well accepted by many reading development researchers (Castles et al., 2018; Hulme & Snowling, 2015; Liberman et al., 1989). Ehri's model of reading development proposed by Ehri (2005b, 2017) further provides a blueprint for how readers become more proficient. In her concept of orthographic mapping, children learn to read by repeatedly forming connections between graphemes and phonemes which map onto meaning. A developmental sequence progressing from the use of visual cues (pre-alphabetic phase) to partial connections (partial alphabetic phase), to complete connections (full alphabetic phase) between all graphemes and phonemes; and finally, to making grapho-syllabic connections (consolidated alphabetic phase) is proposed (Ehri, 2017; Seymour et al., 2003). I will focus on the final phase in this thesis as this is when syllabic connections are more obvious.

In the consolidated alphabetic phase, the mental lexicon consists of an array of letter-sound connections merged into larger processing units such as rimes, syllables, morphemes, and whole words. Children in this phase have been introduced to multisyllabic words and are able to read and spell using grapho-syllabic connections (Ehri, 2017). In addition, they can read new words using analogies from previously learned words in their memory e.g., *j-ump- pump.* Critically, Bhattacharya and Ehri (2004) proposed that between third and fifth grades, decoding multisyllabic words becomes important. This was supported by their study showing an increase in post-test scores of adolescents reading at third to fifth grade equivalent levels after a syllable-intervention compared to those in a control condition.

Ehri's transitional model aligns with most models of reading that predict a shift from letter-by-letter decoding to whole word orthographic lexical access as reading skill improves (Ans et al., 1998; Coltheart, 2006; Grainger et al., 2012; Grainger & Ziegler, 2011).

1.5.4. Models of Multisyllabic Word Reading

While many models of word recognition are fit to monosyllable word data (Coltheart et al., 2001; Seidenberg & McClelland, 1989; Zorzi et al., 1998), the Multiple Trace Memory (MTM) Model accounts for multisyllabic word processing (Ans et al., 1998). In

this model, words and nonwords may be processed via two sequential routes: the global route, and the analytical route. Processing occurs via the analytical route using previously learned associations of whole words and syllabic segments that map print to sound. A key prediction of this model is that the naming latency of nonwords should increase with an increasing number of syllables as each new syllable will require a new visual capture, hence taking more time. Since less skilled readers may have had fewer encounters with words than skilled readers, less skilled readers are inclined to use the analytical route for most words, whereas this route is limited to nonwords or unfamiliar words for skilled readers (Ans et al., 1998).

Another model, the Connectionist Dual Process (CDP++) model has been used to simulate human performance on syllable number effects using the data from the English Lexicon Project (ELP; Balota et al., 2007; Perry et al., 2010). This model also predicts that disyllabic words take longer to read aloud than monosyllabic words by two possible explanatory mechanisms. First, the graphemic parser assigns all graphemes to the first vowel in a two-syllable word. Then, when the second vowel is processed, the graphemes need to be reorganized appropriately. In addition, the second vowel of a disyllabic word is usually inconsistent whereby it has more than one pronunciation in different words, thereby slowing processing.

1.6. Summary and Theoretical Scope

The research evidence and theoretical models summarized in the previous sections of this introduction suggest that much has been learnt about eye movements *a.)* across line boundaries *b.)* during oral reading and *c.)* in developing readers. Therefore, this thesis attempts to integrate these areas to form a holistic understanding of children's reading as measured using simultaneous eye movements and voice recordings. To do this, the research comprised two experiments. Experiment 1 is detailed in Chapter Two while Chapters Three to Six contain data obtained from Experiment 2.

In Chapter Two, I sought to explore how oral reading impacts return-sweep planning and targetting compared to silent reading. While recent studies on return-sweep saccades have focused on silent reading, no research has compared both modalities. Therefore, I asked: *what differences exist in launch and landing positions, corrective saccade probability, and fixation durations before and after the return-sweep between skilled adult readers' silent and oral reading conditions?* Return-sweep saccades could be assumed to be no different from intra-line saccades and so be subject to similar oral

reading costs like intra-line saccades. However, the coordination of the eye and voice during reading aloud may require more effort or cognitive resources when moving between lines and might lead to differences in return-sweep planning and targeting between both modalities.

In Chapter Three, I replicate the development of the EVS as an index of reading development in two ways. First, by investigating and replicating grade effects on the EVS in developing readers. Second, by examining whether the EVS is sensitive to syllable units and whether this changes across grades three, four, and five. The second objective was achieved through the experimental manipulation of target words (one versus two-syllable words). Using a similar manipulation, research in skilled silent reading reported null effects of syllable number on gaze duration. Therefore, I asked *how this effect might be reflected in multiple measures of gaze duration, articulation duration and especially, the EVS and whether these change across grades*. Intermediate processing units such as syllables may mediate the transition from letter-by-letter decoding to whole word reading. If whole word encoding signals skilled reading, then the use of syllable information may change as reading instruction and experience are acquired.

Chapter Four examines how children coordinate their eyes and voice when reading multi-line text aloud. As will be seen, results from Chapter Two reveals marked differences in eye movement behaviour during oral compared to silent reading. This effect is particularly pronounced around return-sweeps, suggesting that additional visual and speech coordinative processes impact return-sweep planning. Therefore, I explored the EVS and its changes within and between lines. Critical to this chapter is examining how the EVS modulates the different fixation populations. Laubrock and Kliegl (2015) showed that the EVS is kept at a reasonable span through oculomotor adjustments such as increases in fixation durations, regression, and refixation probabilities. Consequently, I asked: *does the EVS differentially impact fixation durations adjacent to the return-sweep compared to intra-line fixations*? This chapter also examined how speech processes modulate the EVS.

Owing to the potential utility of the EVS in capturing different aspects of language and cognitive processing and the labour intensity in EVS data processing, Chapter Five detailed the reliability of EVS measures. Additionally, I use an individual differences approach to explore what reading-related skills account for variation in the EVS and eye movements during oral reading.

Chapter Six examines bidirectional lexical influences during oral reading to explore concurrent articulatory influences on eye movement behaviour. Consequently, I primarily

examine the influence of word frequency and length of the articulated word on eye movement behaviour.

Finally, in Chapter Seven, I break down the theoretical and methodological implications of the findings in this thesis for reading development and developmental eye movement research, and highlight the resultant challenges from this work as well as propose recommendations for future studies.

CHAPTER TWO: Return-sweeps in Oral Reading

The following chapter is published as:

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2.1. Abstract

Recent research on return-sweep saccades has improved our understanding of eye movements when reading paragraphs. However, these saccades which take our gaze from the end of one line to the start of the next line, have been studied only within the context of silent reading. Articulatory demands and the coordination of the eye-voice span (EVS) at line boundaries suggest that the execution of this saccade may be different in oral reading. We compared launch and landing positions of return-sweeps, corrective saccade probability and fixations adjacent to return-sweeps in skilled adult readers while reading paragraphs aloud and silently. Compared to silent reading, return-sweeps were launched from closer to the end of the line and landed closer to the start of the next line when reading aloud. The probability of making a corrective saccade was higher for oral reading than silent reading. These indicate that oral reading may compel readers to rely more on foveal processing at the expense of parafoveal processing. We found an interaction between reading modality and fixation type on fixation durations. The reading modality effect (i.e., increased fixation durations in oral compared to silent reading) was greater for accurate line-initial fixations and marginally greater for line-final fixations compared to intra-line fixations. This suggests that readers may use the fixations adjacent to return-sweeps as natural pause locations to modulate the EVS.

2.2. Introduction

Research on eye movements during reading has been dominated by the exploration of silent reading processes. However, much can be learned from oral reading processes, especially since this is the primary modality through which children learn to read (Laubrock & Kliegl, 2015; Vorstius et al., 2014). During reading, we translate visual symbols to sounds by mapping orthography to phonological and semantic representations

stored in our mental lexicon. This process of lexical activation and access has been thought to occur similarly, regardless of whether we read silently or aloud. For instance, visual word recognition processes during naming and silent reading tasks are similarly influenced by several lexical variables (Juel & Holmes, 1981; Schilling et al., 1998). However, while silent reading involves covert or inner speech, oral reading involves overt speech production (Rayner et al., 2012) . This additional articulatory component in oral reading increases reading times. Compared to silent reading, eye movement patterns in oral reading are characterized by an increased number of fixations, longer fixation durations (approximately +50ms), higher refixation probabilities, less skipping, and shorter saccades (6-7 letters vs. 7-9 letters; Anderson & Swanson, 1937; Ashby et al., 2012; Inhoff & Radach, 2014; Kim et al., 2019; Krieber et al., 2017; Rayner, 2009; Vorstius et al., 2014).

Eye movement reading research has also been dominated by single line studies, with few experiments exploring multiline reading and the return-sweep saccades needed for such texts (see Slattery & Parker, 2019; Slattery & Vasilev, 2019). These two research tendencies (silent reading and single line reading) have resulted in a lack of research into oral reading of multiline text, especially with regards to the return-sweeps that move gaze from the end of one line to the start of the next (Parker, Slattery, et al., 2019). Return-sweeps are still not fully understood, and recent evidence suggests that their targeting and execution may be distinct from intra-line saccades (Slattery & Vasilev, 2019). It is known that during silent reading, the first fixation on a line is longer and the last fixation on a line is shorter in duration than intra-line fixations (i.e., those that do not cross line boundaries; Abrams & Zuber, 1972; Parker, Slattery, et al., 2019; Rayner, 1977) . However, when reading aloud, the eye tends to lead the voice in the text as readers make articulatory plans (Buswell, 1920). Because of this articulatory need, and the absence of parafoveal preview information across line boundaries, reading aloud may impact the planning and execution of return-sweeps.

2.2.1. Eye-movements during Oral Reading

Though considered a less mature way of reading, oral reading is common. Developing readers use oral reading to map written text to phonological codes and skilled adult readers may engage occasionally in oral reading when reading difficult texts (Hardyck & Petrinovich, 1970). Although less than 2% of adult respondents from a recent survey read aloud more than they read silently; reading instructions, recipes, shop signs and reading to loved ones are few ways oral reading occurs in adulthood (Duncan & Freeman, 2019).

Fundamentally, oral reading processes mirror silent reading processes in many ways since eye movement measures in both reading modalities are correlated within individuals (Anderson & Swanson, 1937; Søvik et al., 2000) and across individuals of different languages (Brysbaert, 2019). However, there are differences which follow directly from the differences in the rate of silent reading which is ~250 words per minute (WPM) and the rate of conversational speech (~150 WPM). The lower rate of conversational speech reveals speed limitations of the articulatory system. Speech rates may begin to approximate silent reading rates only in trained professionals (e.g., high-speed auctioneers; Rayner et al., 2016). However, for most people and dialogues, speech rates do not approach silent reading rates due to articulatory limitations. Therefore, speech processes may constrain oculomotor processes when the two systems are simultaneously activated. As such, it is perhaps not surprising that oral reading rates lie somewhere in between conversational speech and silent reading rates (~180 WPM; Brysbaert, 2019).

The differences between oral and silent reading rates can be attributed to the time taken to articulate, which is often slower than the time to engage in visual and linguistic processing of text. The slower speed of articulation brings along the need to coordinate the eye and the voice through a continuous adjustment of when and where to move the eyes. Such adjustments are evident in the increase in fixation durations, refixations and regressions based on the width of the eye-voice span (EVS). The EVS is the distance between the eye and the voice and averages about two-words or 16 characters in skilled readers (Inhoff et al., 2011; Laubrock & Kliegl, 2015; Rayner et al., 2012). However, during reading aloud the EVS changes dynamically based on moment to moment reading demands/conditions. When the EVS is too wide at the onset of fixation, the oculomotor system responds by pausing longer to allow the voice to catch up, and if the EVS remains wide at the end of the fixation, regressive saccades are more likely to be triggered (Laubrock & Kliegl, 2015, Inhoff et al., 2011). Therefore, during reading aloud, additional constraints are placed on the oculomotor system by the articulatory system which influence the decision of when and where to move the eyes. One by-product of this is that the relative influence of variables such as word frequency may be reduced during reading aloud (Huestegge, 2010; Vorstius et al., 2014). It would appear that, during oral reading, the decision to terminate a fixation may not solely be determined by word frequency but also by the phonetic characteristics of words and the continuous coordination of the eye and voice (Vorstius et al., 2014, Laubrock & Kliegl, 2015).

The yoking of the eye's forward progress to the voice is likely accomplished by means of controlling the movement of attention which precedes saccadic eye movements

(Rolfs et al., 2010; Shepherd et al., 1986; Zhao et al., 2012). Additionally, it is the pre-saccadic attentional movements that are responsible for parafoveal preview benefits (see discussion below) within the E-Z Reader model (Pollatsek et al., 2006; Reichle et al., 1998). Therefore, the yoked coordination of the eye and voice may limit the amount of parafoveal processing that occurs during oral reading as attention works to hold back the forward progress of the eyes. Indeed, oral reading appears to be less influenced by parafoveal preview manipulations than silent reading. For example, Ashby et al. (2012) manipulated the availability of parafoveal information using a moving window paradigm (McConkie & Rayner, 1975). Windows of either one or three words were presented to participants while they read orally or silently whilst the other words were masked. They found that the availability of accurate parafoveal information improved reading speed in silent reading more than it did for oral reading. Similarly, Inhoff and Radach (2014) investigated the extent to which readers process words in the parafovea using the boundary paradigm (Rayner, 1975). In this paradigm, an invisible boundary is placed before a target word in the sentence to manipulate what parafoveal preview participants receive in the target word location. Once the boundary is crossed, the preview changes to the actual target word. The difference in fixation durations between a valid preview (i.e., the target itself is present) and an invalid preview (i.e., a different string of letters) is called the *preview benefit* (Rayner, 1998). The preview benefit is typically interpreted as a processing advantage that allows readers to initiate recognition processes before a word is fixated (Reichle & Reingold, 2013). Inhoff and Radach (2014) found that preview benefits were smaller in oral compared to silent reading. This further suggests that readers extract less parafoveal information during oral compared to silent reading.

2.2.2. Return-sweep Saccades in Silent Reading

Return-sweep saccades usually launch from and land some five to seven characters away from the right and left margins of successive lines, respectively (Hofmeister et al., 1999; Parker, Nikolova, et al., 2019; Rayner, 2009; Slattery & Vasilev, 2019). Furthermore, compared to intra-line saccades, return-sweep saccades are longer—typically travelling between 40 to 70 characters (Slattery & Vasilev, 2019). The landing position of a return-sweep saccade is influenced by the length of the previous line: with longer lines, landing positions shift to the right (Hofmeister et al., 1999; Parker, Nikolova, et al., 2019; Vasilev et al., 2020). Unlike intra-line saccades, where the target is assumed to be the centre of a word (known as Optimal Viewing Position [OVP]; McConkie et al., 1988), the target of the return-sweep saccade is assumed to be an area relative to the left margin that is

independent of the length of the first word on a line (Slattery & Vasilev, 2019). Furthermore, return-sweep landing positions are influenced by font size information, whereby landing positions in visual angle are shifted rightwards with large compared to small font sizes (Hofmeister, 1998; Vasilev et al., 2021). This effect is independent of the length of the previous line and suggests that readers use global text characteristics to target a location on the new line that maximizes word identification processes (Vasilev et al., 2021).

Compared to intra-line saccades, return-sweep saccades are costly eye movements. Because of their length, they often tend to undershoot their target (McConkie et al., 1988). As a result, many return-sweeps are followed by a corrective saccade that takes gaze closer to the left margin of the line (Ciuffreda et al., 1976; Hofmeister et al., 1999). In fact, this occurs approximately 40-60% of the time (Slattery & Vasilev, 2019). Research shows that the probability of making a corrective saccade is determined by an increase in saccade amplitude as indexed by line length measured in degrees of visual angle where longer lines lead to more corrective saccades (Hofmeister et al., 1999; Vasilev et al., 2021). Return-sweep landing positions closer to the left margin have also been associated with fewer corrective saccades as the magnitude of undershoot error provides retinal feedback to the oculomotor system to determine whether a corrective saccade should be triggered (Hofmeister et al., 1999; Vasilev et al., 2021). Return-sweeps may also incur a large cost if they are launched too early and require a long-distance regression back to the end of the prior line, especially because line boundaries do not usually coincide with sentence boundaries (Kuperman et al., 2010).

Recent work by Parker, Slattery, et al. (2019) has also shown that, during silent reading, children (6 to 9 years) launch their return-sweeps from closer to the end of the line and land closer to the beginning of the new line compared to adults. This may occur because developing readers are less efficient in parafoveally processing words. Therefore, they may have to fixate more extreme regions of the lines to compensate for this. Furthermore, Parker, Slattery, et al. (2019) found that children make more corrective saccades following their return-sweeps, even though they land closer to the beginning of the new line, presumably due to their need for greater foveal processing of line-initial text.

The fixations adjacent to the return-sweep give information about the distinctive feature of this long reading saccade. Line-final fixations which occur prior to launching the return-sweep saccade are characteristically shorter than intra-line fixations (Abrams & Zuber, 1972; Parker, Nikolova, et al., 2019). These fixations have been thought to be

shorter in duration due to either a lack of parafoveal information at line boundaries (Rayner, 1977) or due to return-sweep planning (Kuperman et al., 2010; Mitchell et al., 2008). There are two distinct types of fixations that follow return-sweeps: 1) undersweep fixations, which are followed by a corrective leftward saccade; 2) accurate line-initial fixations, which are followed by a rightward saccade. Accurate line-initial fixations are longer than intra-line fixations, likely because they land on text that has not been processed parafoveally (Heller, 1982; Parker et al., 2017). However, undersweep fixations are shorter than other reading fixations, as they are terminated quickly in order to move the eye to a better viewing location (Abrams & Zuber, 1972; Hofmeister et al., 1999; Parker et al., 2020; Parker, Slattery, et al., 2019).

2.2.3. The Present Study

The present study explored how reading aloud influences return-sweeps compared to reading silently. This is of particular interest because oral reading involves the coordination of the eye with the voice for fluent reading. In addition to the natural lagging feature of speech processes, readers' eye movements are functionally ahead of the voice to obtain a sufficient view of upcoming words and to prepare phonological and articulatory codes for speech output (Buswell, 1920; Levin & Turner, 1966). However, at the end of the line, access to upcoming words (i.e., those at the start of the next line) is largely limited (Parker et al., 2017). Since return-sweeps are costly eye movements, the oculomotor system is saddled with the decision of how long to wait at the end of the line before moving to the next line so that new words can be processed and stored for articulation. Moving too early could result in an unreasonably large EVS. Wait too long, and fluent reading may be disrupted. Thus, a modulation of the EVS might impact the way return-sweeps are executed in oral reading compared to silent reading. This eye-voice coordination account where readers are monitoring the span between the voice and the eye to ensure it is neither too narrow nor too wide allows us to make predictions regarding how return-sweep spatial parameters (launch and landing positions) and temporal measures (fixation durations adjacent to return-sweep saccades) may differ between silent and oral reading. Additionally, previous evidence has suggested that the EVS decreases towards the end of lines (Buswell, 1920; Fairbanks, 1937; Quantz, 1897), just before the return-sweep saccade would be made.

First, oral reading is characterized by shorter saccades and higher refixation rates (De Luca et al., 2013; Rayner, 2009), likely driven by the ongoing need to allow the voice to catch up with the eyes (Laubrock & Kliegl, 2015). Because of this speech lag, less

attention may be given to upcoming words, thus reducing parafoveal processing compared to silent reading conditions. As a result, readers should be less likely to skip words. Therefore, words closest to the left and right margins should be more likely to receive fixations in oral reading compared to silent reading. Furthermore, if readers aim to keep the eyes from travelling far ahead of the voice through refixations, the likelihood that fixations will be nearer to the left and perhaps, right margin, becomes greater. Consequently, identical to return-sweep planning in children who have a similar need for foveal inspection (Parker, Slattery, et al., 2019), we expect return-sweep launch and landing positions to occur closer to the right and left margin respectively in oral reading compared to silent reading.

Second, since our expectations regarding launch and landing positions mean that readers may aim to target regions closer to the left margin, return-sweeps will be planned to travel farther in oral reading (thus increasing the susceptibility to undershoot errors). Therefore, the probability of making a corrective saccade should be greater in oral reading. This is because the farther the saccade target, the greater the probability of an undershoot (Abrams & Zuber, 1972; Kuperman et al., 2010). Furthermore, reduced parafoveal processing during reading aloud should mean that readers rely more on foveal processing and require more frequent corrective saccades to foveate line-initial words.

Third, we would expect fixation durations to be longer when reading aloud than when reading silently because the need for articulation slows down the oculomotor system. More importantly, we expect the increase in fixation durations associated with reading aloud to be greater for line-final fixations and accurate line-initial fixations than for intra-line fixations, because the system monitoring the EVS may use the fixations adjacent to the return-sweep as a natural pause to allow the voice to catch up with the eyes. Allowing the voice to catch up at the line-final fixation may help prevent a costly regression after the return-sweep saccade is made either due to a wide EVS at the end of the accurate line-initial fixation (Laubrock & Kliegl, 2015) or insufficient processing of line-final information. This wait time is particularly likely because regressions across lines are less common than regressions within lines (Ehrlich & Rayner, 1983; Rayner, 1998). This is especially plausible if fixations prior to return-sweeps function to process linguistic information (Rayner, 1977), rather than just being concerned with oculomotor planning (Mitchell et al., 2008). Such regressions at line boundaries may have a ripple effect on oral reading fluency and so the oculomotor system may attempt to prevent this from happening by modulating fixation durations adjacent to the return-sweep. Since return-sweeps launch and land about 5 – 7 characters from both margins (Hofmeister et

al., 1999; Parker, Nikolova, et al., 2019; Rayner, 2009; Slattery & Vasilev, 2019), it follows that the intervening number of characters between return-sweep launch and landing sites may be greater than the average intra-line saccade length (10-14 vs 7-9 characters) during silent reading. This difference would lead to a wide, and potentially obvious, EVS at the start of the line which the oculomotor system may aim to compensate for by increasing wait time at this location. Undersweep fixation durations, which are thought to result from oculomotor error (Hofmeister et al., 1999; Slattery & Parker, 2019), are expected to be unaffected by reading modality.

2.3. Method

2.3.1. Participants

Forty students (21 female) participated for course credits or £10 compensation. Their average age was 22 years (*SD*= 5.96 years: range 18-45 years). All participants were fluent English speakers who reported normal or corrected to normal vision and no prior diagnosis of reading disorders. All participants were naive as to the purpose of the experiment. The study was approved by Bournemouth University Research Ethics Committee (ID 26561).

2.3.2. Materials and Design

The reading stimuli consisted of 40 multiline passages (see Figure 2.1 for an example). On average, stimuli contained approximately 11 lines of text (range: 9-12). Each line had an average of 64 characters (range: 5- 78). The experiment had a single factor within subject design with Reading Modality (Silent vs. Oral) as the independent variable. The data were collected as part of an experiment that examined the role of abbreviations on eye movements during oral and silent reading. In addition to Reading Modality, this within subject design included factors for target Word Frequency, target Abbreviation Type. The target word variables were not considered for the current analysis.

The assignment of conditions to sentences was counter-balanced with a full-Latin square design across all participants. The two reading modalities were blocked, and items appeared in a pseudo-random order within each block. Half of the participants read silently first, and the other half read aloud first.

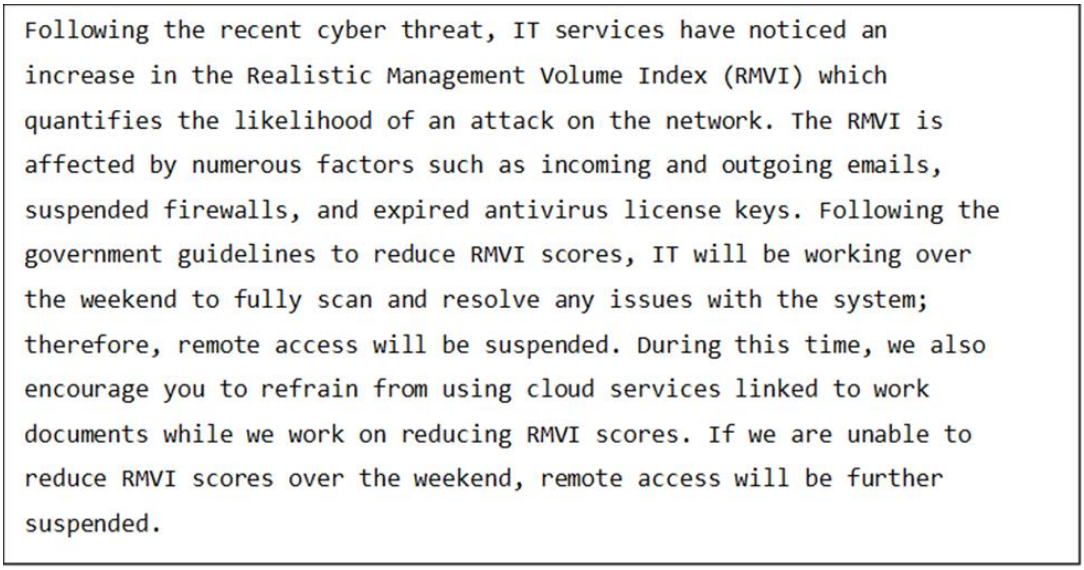

Figure 2.1. An example paragraph used in the experiment

2.3.3. Apparatus

Eye movements were recorded with an SR Research EyeLink 1000 eye-tracker with sampling frequency of 1000Hz. Although viewing was binocular, only the right eye was recorded (except for three participants who had their left eye recorded due to tracking problems). Participants' head was held stable using a forehead rest without the chin rest to allow for easy articulation while reading aloud. This setting was also adopted for the silent reading block. The stimuli were presented using a Cambridge Research Systems LCD++ monitor with a 1920 x 1080 screen resolution and a 120 Hz refresh rate. The text was formatted in an 18-point monospaced Consolas font, which appeared as black letters over a white background. The text was doubled spaced, justified to the left and presented in the middle of the screen vertically and with a 500-pixel offset horizontally. The eye-to-screen distance was 80cm. At this distance, each letter subtended ~0.32 º horizontally.

The experiment was programmed in MATLAB R2014a (MathWorks, 2014) using the Psychtoolbox v.3.0.11 (Brainard, 1997; Pelli, 1997) and Eyelink (Cornelissen et al., 2002) libraries. The experiment was run on a Windows 7 operating system.

2.3.4. Procedure

The experiment began after participants gave written consent and verbal instructions were given. Calibration and validation accuracy were kept at < 0.40º and a recalibration was done whenever the drift check fell below this level, and after every 10 trials during the

experiment. Participants were asked to read the passages for comprehension either silently or aloud, depending on the instruction that appeared before the blocks. The experiment began with two practice trials during which participants read silently.

Each item was followed by a multiple-choice comprehension question with 4 options to ensure understanding of the text. Participants clicked the left button of the mouse to indicate they had finished reading the text and to answer the comprehension questions. The questions were either asking for specific information or the general gist of the passage. An example question for the item above (Figure 2.1) is *"What affects the likelihood of an attack?*", with four options: hardware, corrupt USB devices, careless formatting, and suspended firewalls. All participants were offered to take a short break after every 10 trials.

2.3.5. Data Analysis

Eye movement data were pre-processed using Eye-doctor v.0.6.5 (Stracuzzi & Kinsey, 2009) to align vertical fixations on the correct line and the EMreading R package (Vasilev, 2018) software was used to extract fixation data for the analysis.

Four measures were analysed when comparing return-sweeps in oral and silent reading:

1. *Launch position*: The number of characters from the end of the line that the return-sweep saccade started.
2. *Landing position*: The number of characters from the start of the new line that the return-sweep saccade ended.
3. *Corrective saccade probability*: The likelihood that a return-sweep saccade is immediately followed by at least one additional leftward saccade.
4. *Fixation durations*: The duration of the four distinct types of fixations (Parker & Slattery, 2021; Parker, Slattery, et al., 2019)
    a. Intra-line fixations: those not adjacent to a return-sweep saccade
    b. Line-final fixations: those immediately prior to a return-sweep saccade
    c. Accurate line-initial fixations: those immediately following a return-sweep saccade given that the fixation is followed by a rightward saccade.
    d. Undersweep fixations: those immediately following a return-sweep saccade given that the fixation is followed by a leftward corrective saccade.

The data were analysed using the lme4 package v.1.1-21 (Bates, Mächler, et al., 2015) in R software v.4.0.3 (R Core Team, 2019). In the launch and landing position models, reading modality was a predictor and sum contrast coding was used (Oral: 1, Silent: -1). Launch distance (calculated as number of characters from the left margin) was centred with mean of 0 and was included as a covariate in the landing position and corrective saccade probability models. In the fixation duration models with Fixation type (Intra-line, Line-final, Accurate line-initial & Undersweep) as predictor, treatment contrast coding was used, where intra-line fixations were the baseline. Fixation durations were log-transformed. A full random structure with random slopes and intercepts for participants and items was initially applied (Barr et al., 2013). The maximal model was trimmed by removing higher order interaction terms and components with the least amount of variance in the random effects structure successively until convergence was achieved. The results were considered as statistically significant if the $|t|$ and $|z|$ values were ≥ 1.96. Cohen's d effect sizes are also reported.

2.4. Results

All participants achieved at least 70% on the comprehension questions, indicating that they read the passages for meaning (M= 85.3% SD= 35.4% range: 72.5-95%). Comprehension accuracy was significantly greater in oral reading than silent reading (b = 0.85, SE = 0.16, t = 5.3, p <0.01). Fixations less than 80ms that occurred within one-character space of a temporally adjacent fixation were combined with that fixation. Ten trials were removed due to tracking loss and accidental button presses (0.37%) and a total of 32 lines were removed from trials due to data loss (0.04%). Blinks led to the exclusion of 13.74% of fixations. Fixations less than 80ms which were not merged with an adjacent fixation (1.41%), fixations greater than 1000ms (0.35%), or fixations occurring outside the screen bounds (0.01%) were all discarded. These exclusions impacted the different fixation types similarly. This left a total of 84.07% of fixations for analyses (13738 return-sweep saccades) which were evenly distributed across experimental conditions. Descriptive statistics for different measures of oral and silent reading are reported in Table 2.1 for general information as these are not part of the statistical analyses. Descriptive statistics related to return-sweep saccades are shown in Table 2.2

Table 2.1. Mean and Standard Deviations (in Parenthesis) for eye movement measures across oral and silent reading

Measures	Oral	Silent
Fixation duration	258 (131.51)	226 (99.85)
Single fixation duration	277 (158.15)	234 (109.61)
First fixation duration	271(156.96)	230 (109.45)
Gaze duration	342 (225.43)	267 (150.05)
Total viewing time	414 (285.88)	324 (234.27)
Progressive saccade length*	6.99 (4.32)	8.66 (4.95)
Return-sweep length	57.7(7.59)	55.1(9.31)
Skipping probability	0.13 (0.33)	0.23 (0.42)
Regression probability	0.30 (0.46)	0.31 (0.46)
Reading rate (wpm)	156 (23.73)	241 (72.28)
Comprehension accuracy (%)	89.5 (0.31)	81.1 (0.39)

Note. Saccade length and Return-sweep length are in number of characters. * Progressive saccade length excludes return-sweeps.

2.4.1. Return-sweep Saccade Spatial Measures

The results from the (generalized) linear mixed model ((G)LMM) are shown in Table 2.3 and illustrated in Fig. 2.2 There was a main effect of reading modality on return-sweep saccade launch position (Cohen's d = -0.23, 95% CI [-0.53, 0.08]). When participants read aloud, they launched their return-sweeps from closer to the end of the line than when they read silently. Furthermore, there was a main effect of reading modality on return-sweep saccade landing position (Cohen's d= -0.18, 95% CI [-0.35, -0.01]); return-sweeps landed closer to the beginning of the new line during oral reading compared to silent reading. When considering the main effect of launch distance (i.e., the distance in characters from the left margin where the return-sweep saccade is launched), landing position shifted towards the left margin, the closer from the left margin the return-sweep saccade was launched, but this was only marginally significant. Similarly, there was a marginal two-way interaction between launch distance and reading modality.

Additionally, there was a main effect of reading modality on corrective saccade probability (Cohen's d= 0.15, 95% CI [-0.03, 0.32]). The probability that a return-sweep saccade is followed by a leftward corrective saccade was greater for oral compared to

silent reading. There was also a main effect of launch distance from the left margin, indicating that the greater the launch distance, the higher the probability of making a corrective saccade. However, there was no interaction between launch distance and reading modality on corrective saccade probability.

Table 2.2. Means and Standard Deviations (in Parenthesis) for Return-sweep Saccade Spatial and Temporal Measures

Return-sweep spatial measures		Oral	Silent
Launch position		3.67 (6.15)	5.17 (6.99)
Landing position		5.69 (4.32)	6.64 (5.53)
Accurate line-initial		2.74 (3.11)	3.71 (3.90)
Undersweep		6.91 (4.15)	8.30 (5.58)
Corrective saccade probability		0.71 (0.46)	0.64 (0.48)
Return-sweep temporal measure	**Fixation types**		
Fixation duration (ms)	Intra-line	263 (130.79)	231 (99.16)
	Line-final	237 (135.81)	204(105.85)
	Accurate line-initial	338 (142.60)	281 (97.08)
	Undersweep	152 (55.94)	150(43.74)

Note. Launch position was measured in number of characters from the end of the line, landing position in number of characters from the beginning of the line, corrective saccades as the probability of making a leftward saccade immediately following the return-sweep saccade.

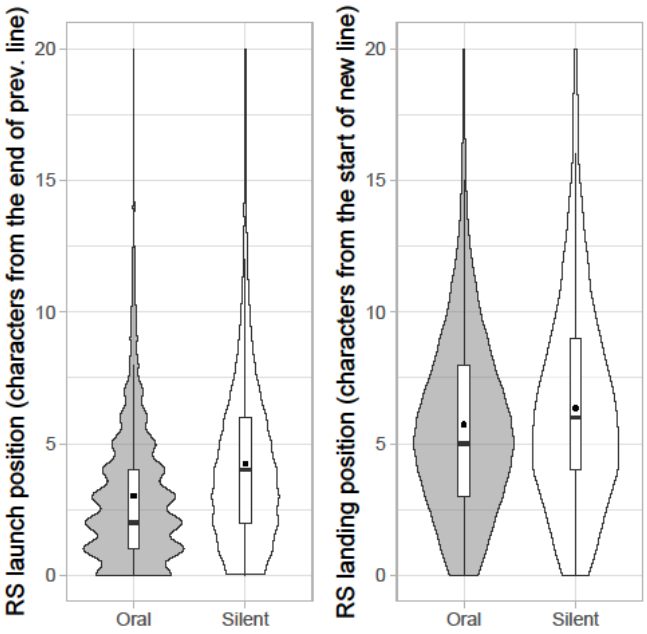

Figure 2.2. Violin plots with box plots embedded showing the distribution of return-sweep saccade launch position (a) and landing position (b). Centre of box plots indicates median, while points indicate the mean.

Table 2.3. (G)LMM Analyses Showing Launch Position, Landing Position and Corrective Saccades as a Function of Reading Modality and Launch Distance

Fixed effects	Launch position [a]			Landing position [b]			Corrective saccades [c]		
	b	SE	t	b	SE	t	b	SE	z
Intercept	4.42	0.26	**16.85**	6.13	0.42	**14.58**	0.87	0.15	**5.87**
Modality	-0.75	0.10	**-5.81**	-0.59	0.14	**-4.16**	0.13	0.05	**2.67**
Launch distance				0.07	0.04	*1.67*	0.14	0.04	**3.36**
Modality* Launch distance				0.07	0.04	*1.66*	0.04	0.02	1.60

Note. Statistically and marginally significant *t*/*z* values are formatted in bold and italics respectively. Return-sweep launch distance measured from the left margin was centred to a mean of 0. Model structures for dependent measures are shown below:

a Launch position ~Modality+ (1+Modality | sub) +(1+Modality | item)

b Landing position ~Modality Launch distance + (1+Modality | sub) +(1 | item)*

*c Corr. saccade probability ~Modality *Launch distance+ (1+Modality+ Launch distance | sub) +(1+Launch distance | item)*

2.4.2. Return-sweep Saccade Temporal Measures

The LMM results are shown in Table 2.4 and illustrated in Figure 2.3. There was a main effect of reading modality as fixation durations in oral reading were generally longer than during silent reading (Cohen's *d*=0.26, 95% CI [0.02, 0.51]). Furthermore, the analyses revealed main effects of fixation types. Specifically, accurate line-initial fixation durations were longer (Cohen's *d*= 0.48, 95% CI [0.17, 0.78]) while line-final (Cohen's *d*= -0.24, 95% CI [-0.52, 0.04]) and undersweep (Cohen's *d*= -0.96, 95% CI [-0.35, -0.57]) fixations were shorter than intra-line fixations. Crucial to our hypotheses, we found reading modality by fixation type interactions. Compared to the reading modality effect on intra-line fixations, the modality effect was marginally greater for line-final fixations. However, it was significantly greater for accurate line-initial fixations and significantly smaller for undersweep fixations. The size of the undersweep modality interaction (-.023) nearly counters the modality main effect (.024) indicating a lack of modality effect for undersweep fixations.

Table 2.4. LMM Analyses Showing Fixation Durations as a Function of Reading Modality and Fixation Types

Fixed effects	Fixation duration*		
	b	SE	t
Intercept	2.3542	.0061	**386.0729**
Modality	.0241	.0004	**56.7387**
Accurate line-initial fixation	.0993	.0026	**38.1943**
Line-final fixation	-.0640	.0015	**-42.2308**
Undersweep	-.1909	.0018	**-104-.4191**
Modality: Accurate line-initial fixation	.0075	.0026	**2.8968**
Modality: Line-final fixation	.0029	.0015	*1.8967*
Modality: Undersweep fixation	-.0233	.0018	**-12.7636**

Note. Statistically and marginally significant *t*/*z* values are formatted in bold and italics respectively.

**log10(fix_dur) ~ fix_type * Modality + (1 | sub) +(1 | item)*

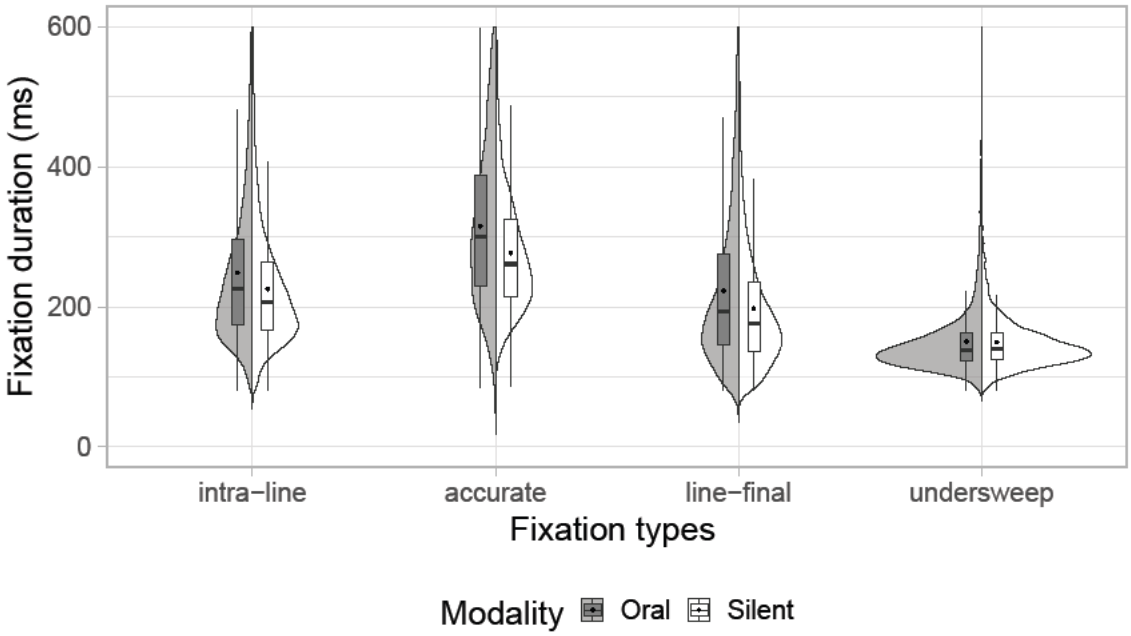

Figure 2.3. Split violin plots with box plots embedded showing the distribution of fixation durations by reading modality and fixation types. Centre of box plots indicates median while points indicate the mean. Y- axis limit was set at 600ms for graphical purposes as upper bound in analyses was 1000ms.

2.5. Discussion

The present study investigated how reading modality (silent vs. oral) affects return-sweep saccade planning and execution in adult readers. We found that readers launched their return-sweeps from closer to the right text margin and terminated it at a position that is closer to the left text margin of the next line during oral compared to silent reading. Additionally, the probability of making a corrective saccade was higher in oral reading compared to silent reading. Finally, while we replicated the robust modality effect on fixation durations, we also show for the first time that this effect was significantly greater for accurate line-initial fixations and marginally greater for line-final fixations compared to intra-line fixations.

Launch and landing positions closer to the right and left text margins respectively indicate that the amplitude of the return-sweep saccade is longer in oral reading than silent reading. During oral reading, articulatory constraints on the oculomotor system may limit pre-saccadic attentional shifts to parafoveal words (Pollatsek et al., 2006; Rolfs et al., 2011). This view is compatible with reduced capacity for parafoveal processing in oral

reading compared to silent reading within lines (Ashby et al., 2012; Inhoff & Radach, 2014; Pan et al., 2017). Because, line boundaries are also influenced by this kind of processing, readers may foveate closer to the left and right margins to process the letters there. EVS modulation via return-sweep launch and landing sites may also occur so readers' progressive saccades will span a similar number of characters when moving within lines and across lines. In this study, the number of new letters taken in by the visual system as evidenced by intra-line progressive saccade length was 6.99 and 8.66 characters for oral and silent reading respectively (see Table 2.1). We can calculate the progressive span of return-sweep saccades by summing the number of characters to the right of its launch position with the number of characters to the left of its landing position. Doing this, we see that accurate return-sweeps have a progressive span of 6.41 and 8.88 characters for oral and silent reading respectively (see Table 2.2). This indicates that roughly the same number of characters were available for processing between fixations for both intra-line and return-sweep saccades. Furthermore, reading modality influenced the progressive movement of the eyes in the text similarly for intra-line and return-sweep saccades. Overall, these results are consistent with the proposition that oral reading may be a less risky reading strategy compared to silent reading because words are skipped less often (McGowan & Reichle, 2018; McGowan et al., 2014; Rayner, Chace, et al., 2006).

Early research suggested that the distance from which a return-sweep is launched may influence its landing position. Though no inferential statistics were presented, Hofmeister et al. (1999) showed that the mean launch and landing positions of return-sweeps shifted rightwards with increasing line length. We found a marginally significant launch distance effect on landing positions in this direction. Additionally, we found a marginal interaction between launch distance and reading modality. As launch site shifted to the left, so did the landing site for reading aloud but this relationship was largely absent for silent reading. Examining the scatterplot for this model revealed that this interaction may have been driven by three cases of shallow return-sweep saccades (i.e., return-sweeps that launched and landed towards the middle of lines) in the silent reading condition. Such an influence may mirror inconsistencies found with launch distance effects on return-sweeps (see Slattery & Vasilev, 2019; Vasilev et al., 2021). Considering these, more research is needed to clarify the influence of launch distance on return-sweep landing positions in skilled adult reading.

While the launch distance effect on landing position was marginal, the launch distance effect on corrective saccade probability was significant. The greater the distance from the left margin the return-sweep saccade was launched, the greater the probability

of making a corrective saccade. This agrees with what has been found with previous research (Hofmeister et al., 1999; Slattery & Vasilev, 2019; Vasilev et al., 2021) and reflects the fact that undershoots are increasingly likely to occur the farther away the eyes are from the saccade's target location.

Reading modality also significantly influenced corrective saccade probability, which was higher in oral compared to silent reading. This result is similar to the finding that children are more likely to initiate such corrective left-ward saccades than adults, presumably to enable more precise foveal encoding of words at line extremities (Parker, Slattery, et al., 2019). Despite the tendency to foveate closer to the left margin at the start of a new line when reading aloud, our readers nevertheless made more corrective leftward saccades in this condition. This may be explained by assuming that readers target an area closer to the left margin when reading aloud to enable foveal processing of line-initial characters, resulting in longer intended saccades and therefore increased saccadic error (McConkie et al., 1988). This increased saccadic error would then result in an increased need for corrective leftward saccades (Slattery et al., in preparation). The increase in corrective saccade probability may also modulate the eye-voice span as readers may be more likely to initiate a corrective saccade if the EVS at the end of the last fixation on the line was wide. In this way, corrective saccades may serve a similar function as regressions in modulating the EVS (Laubrock & Kliegl, 2015).

A considerable amount of work has shown that fixation durations are longer when reading aloud compared to when reading silently (Anderson & Swanson, 1937; Krieber et al., 2017; Laubrock & Kliegl, 2015; Rayner, 2009; Vorstius et al., 2014). Our results are clearly consistent with these studies. This suggests that the oculomotor system may delay progressive saccade generation to prevent a wide EVS (Inhoff et al., 2011; Laubrock & Kliegl, 2015). As in previous return-sweep studies, we found that compared to intra-line fixations, line-final and undersweep fixations were shorter and accurate line-initial fixations were longer (Abrams & Zuber, 1972; Heller, 1982; Hofmeister et al., 1999; Parker et al., 2020; Parker, Nikolova, et al., 2019, Rayner, 1977). However, what remained unknown was how the reading modality effect may differentially influence fixations adjacent to the return-sweep. We hypothesized that the increase in fixation durations in oral compared to silent reading would be greater for line-final fixations and accurate line-initial fixations compared to intra-line fixations due to EVS coordination at line boundaries. As expected, the reading aloud cost was significantly greater for accurate line-initial fixation durations (57ms) and marginally greater for line-final fixations (33ms) during oral reading when compared to intra-line fixations (32ms). The implication of this

finding is that the oral reading cost, while pervasive throughout the text being read, was greater around return-sweeps (particularly after them), suggesting that these fixations offer a suitable opportunity for EVS modulation.

The fixations intervening between the return-sweep and corrective saccade has been called undersweep fixations (Parker et al., 2017; Parker et al., 2020). Whether or not these fixations are involved in ongoing linguistic processing has been a subject of recent research (Parker et al., 2020; Slattery & Parker, 2019). Our results reveal that the reading modality effect was absent for undersweep fixations (2ms). This is in line with the proposition that these fixations result from oculomotor error (Hofmeister et al., 1999; Slattery & Parker, 2019). The implication of this finding is that undersweep fixations are not sensitive to the additional articulatory demands of oral reading nor the modulation of the EVS.

In summary, the fixation duration results suggest that the fixations around return-sweeps (line-final and accurate line-initial fixations) may offer a natural pause in the acquisition of new linguistic information and may modulate the EVS during oral paragraph reading. The coordination of the eye and voice causes a reliance on foveal processing rather than parafoveal processing in oral reading which reflected in the launch position, landing position and corrective saccade probability results. It is apparent that oral reading imposes restrictions on eye movements not only because of the time required to articulate words but also the time allocated to articulatory pauses (Godde et al., 2021). These pauses are essential not just for intelligible speech production (Quantz, 1897) but also physiologically, articulation occurs mostly during periods of exhalation and not inhalation (Huey, 1908). Paragraph reading involves the integration of meaning across multiple sentences and lines (Cook & Wei, 2019). While longer fixation pauses are made at sentence boundaries due to sentence wrap up effects (Kuperman et al., 2010; Tiffin-Richards & Schroeder, 2018), intermittent pauses are also made by the articulatory system at phrase units, sentence boundaries and punctuation marks during oral reading. In addition to this, we propose that, during oral reading, the oculomotor system may also use line boundaries, as pause points to ensure a reasonable EVS. Although, it could also be that reading tasks that generally require more attention to word processing, such as oral reading, may cause saccade generation at the start and end of lines to be delayed. To explore the plausibility of this and increase our understanding of return-sweeps, future research may seek to compare the influence of different reading tasks varying in cognitive demands (e.g., skimming, proofreading, or reading while listening; Valentini et al., in preparation), on return-sweep saccade execution and targeting.

2.6. Chapter Overview

In this chapter, we examined differences in skilled reader's return-sweep planning and execution during oral and silent reading. It was reported that launch and landing positions were closer to the right and left margins, respectively and corrective saccades were more frequent in oral compared to silent reading. The fixations around the return-sweep, namely: line-final fixations and accurate line-initial fixations were impacted more by oral reading compared to intra-line fixations. We concluded that this pattern of increased fixation times around the return-sweeps served to modulate the eye-voice span. Therefore, before investigating this relationship (see Chapter 4), we found it necessary to undertake a developmental exploration of the EVS. More importantly, we wanted to examine whether the EVS was sensitive to syllable units which are representational units during speech production. These will be the focus of the next chapter.

Chapter 3

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3. Syllable Units During Oral Reading

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See https://eprints.bournemouth.ac.uk/39423/

4. The Eye-voice Span within and between Lines

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See https://eprints.bournemouth.ac.uk/39427/

Chapter 5

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5. Reliability and Individual Differences in the Eye-voice Span and its Modulation

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Chapter 6

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6. Bi-directional Lexical Influences during Oral Reading

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CHAPTER SEVEN: General Discussion

There is currently a dominance of silent reading research in exploring underlying developmental and skilled reading processes using eye-tracking technology (Blythe & Joseph, 2011; Blythe et al., 2009; Johnson et al., 2018; Joseph et al., 2009; Joseph et al., 2013; Pagan et al., 2016; Rayner, 1986; Reichle et al., 2013). Collectively, these studies show that the differences in eye movement behaviour between children and adults are primarily due to linguistic proficiency (Blythe, 2014; Leinenger et al., 2017; Reichle et al., 2013). There are also more oral reading eye-tracking studies in children compared to adults (Hyona & Olson, 1995; Kim et al., 2019, 2020; Marx et al., 2015; Marx et al., 2016; Vorstius et al., 2014). This discrepancy is expected as children read aloud more often than adults do. In reviewing these studies, it is evident that eye movements are slower during oral compared to silent reading (Anderson & Swanson, 1937; Kim et al., 2019; Vorstius et al., 2014). This happens because of the continuous coordination of the eye and the voice. The eye-voice span provides a good indicator of this coordination, but there is currently a dearth of developmental research on the EVS using modern-day eye-tracking equipment and statistical techniques. Early research has shown that a developmental trend exists for the EVS where older and more experienced readers have a larger span compared to younger readers (Buswell, 1920; Levin & Turner, 1966). In addition, the EVS has been associated with low-level visual processing, higher-order semantic integration and cognitive skills such as working memory (Gordon & Hoedemaker, 2016; Laubrock & Kliegl, 2015; Levin & Turner, 1966). Therefore, the EVS has the potential to unravel underlying reading processes in children who mostly read aloud.

Limited research also exists on understanding the eye movements that take our gaze from the beginning of one line to another (i.e., return-sweep saccades). The recently growing body of work in skilled readers suggests that these saccades are very different from intra-line saccades (Adedeji et al., 2021; Parker et al., 2017; Parker, Nikolova, et al., 2019; Parker & Slattery, 2019, 2021; Slattery & Parker, 2019; Slattery & Vasilev, 2019; Vasilev et al., 2021). There are relatively few studies exploring return-sweeps of developing readers (Molina et al., 2020; Parker et al., 2020; Parker, Slattery, et al., 2019; Trauzettel-Klosinski et al., 2010). Intra-line saccade targetting is similar in children and adults (Aghababian & Nazir, 2000; Joseph et al., 2009). However, return-sweep saccade targetting differences exists between both groups suggesting that return-sweep saccades may be guided by linguistic and/or oculomotor proficiency. What remained unknown

prior to this thesis was how return-sweep targetting differed in oral compared to silent reading, and if there are differences, what role the EVS plays. Therefore, the current thesis provided an independent and systematic examination of the EVS and its relationship with return-sweep saccades during reading development. This work is essential to clarify *(i)* whether the EVS effect on eye movements of skilled readers can be extended to children and whether such effects impact upon return-sweep saccades, *(ii)* whether developmental changes in the EVS reflect sub-lexical/lexical processing units, *(iii)* whether the EVS can tell us more about the reading process than eye movements alone.

Accordingly, this final chapter will begin with a summary of key findings from all five studies, highlighting the novel contribution each one makes to reading research. Then, I will discuss the theoretical, methodological and developmental implications of these findings. Challenges and considerations for future studies will be discussed thereafter. Finally, this chapter and thesis will end with concluding remarks.

7.1. Summary of Key findings

7.1.1. Chapter 2: Return-sweep saccades in oral reading

The first experiment presented in Chapter 2 (Adedeji et al., 2021) investigated differences in return-sweep planning and execution between oral and silent reading modalities for skilled readers. Previous research has primarily established the characteristics of return-sweep saccades. First, they are long saccades prone to undershoot errors and are targeted towards an area of the left margin that optimises word recognition processes. Second, line-final fixations that precede return-sweeps are shorter than intra-line fixations, while line-initial fixations could either be longer (accurate line-initial fixations) or shorter (undersweep fixations) than intra-line fixations. I extended these findings by showing that the return-sweep saccade is much longer during oral than silent reading due to launch and landing sites that are closer to the margins. In addition, corrective saccades or undershoot errors are more likely during oral reading compared to silent reading. Importantly, I report that the fixations adjacent to the return-sweep (i.e., accurate line-initial and line-final fixations) are more affected by oral reading compared to intra-line saccades. That is, the skilled readers in the study tended to wait more at line boundaries in response to an additional articulatory requirement compared to within the lines. This finding was attributed to a greater need for eye-voice synchronisation at line boundaries where readers may pause longer with larger compared to smaller EVS (Laubrock & Kliegl, 2015).

Therefore, it was proposed that line boundaries may present opportunities for the voice to catch up with the eyes before executing a costly return-sweep saccade.

7.1.2. Chapter 3: Syllable Units during Oral Reading

With a clear idea of one critical factor that drives oral reading times, i.e., the EVS, the second experiment in Chapter 3 sought to understand reading development through a developmental exploration of the EVS. First, by replicating grade changes in the EVS and second, by investigating whether the EVS reflects sublexical phonological representations. To achieve this goal, I used the syllable unit, the critical representational unit on which speech-motor planning and programming occurs (Levelt et al., 1999; Levelt & Wheeldon, 1994). I also investigated developmental changes in using syllable information. In this study, developing readers in grades three, four and five read short passages (two lines) aloud with embedded target words of one or two syllables as their eye movements and voices were recorded. Offline measures of reading-related skills (TOWRE-word reading, WIAT-Spelling, RAN/RAS and WASI-II) were collected.

Three dependent measures were examined to track the timeline of word processing from the onset of gaze to the end of articulation. I replicated grade changes in the gaze duration, EVS, and articulation duration for grades four and five. These children also differed in their word reading efficiency scores. However, there were no EVS, gaze duration or articulation duration differences for grades three and four. Furthermore, children in grade three and four did not differ in their average reading efficiency scores. I interpreted these findings as evidence that linguistic proficiency is the primary driver of the eye movements and speech-related processes that govern the EVS during oral reading, rather than oculomotor or speech-motor changes associated with age. I also found syllable number effects for gaze duration that remained consistent across the three grades. Specifically, gaze duration on one-syllable words was longer than on two-syllable words, in contrast to our expectations. This result supports a facilitatory influence of syllable number rather than an inhibitory one. Sensitivity to sub-syllabic units was highlighted as a potential explanation for this finding. Importantly, I did not find any syllable number effect on the EVS, and there was no interaction with grade.

7.1.3. Chapter 4: The Eye-voice Span within and between Lines

In Chapter 4, I extended the work in Chapter 2 by considering how the EVS may differentially impact four fixation types during children's multiline text reading. A large EVS is adjusted through increased fixation durations, refixations and regressions in

skilled readers (Inhoff et al., 2011; Laubrock & Kliegl, 2015). I contributed to this knowledge base by showing that the same mechanism operates for children with at least two years of reading instruction (i.e., 7-year-olds in third grade). Interestingly, I also provided the first evidence of the modulation of the EVS through articulatory mechanisms. Articulation rates were found to increase when the EVS was large compared to when it was small, suggesting that the voice does not proceed at a steady pace, but can speed up when the EVS is too large. This finding confirms Fairbank's (1937) assertion that the voice is in the service of shortening or widening the EVS and strengthens a joint modulation account of the EVS.

Previous return-sweep research in children's silent reading showed no differences in the line-final speed-up effect between children and adults (Parker, Slattery, et al., 2019). That is, the difference between line-final and intra-line fixation durations were similar between children and adults. In this chapter, I provided novel evidence that there could be developmental differences in this effect during oral reading. Specifically, line-final speed-up effects were only observed for children in grade five. This result suggests that younger children may find line-final regions more disruptive to the reading process compared to older children. This finding is consistent with grade two children showing no line-final speed-up effects compared to the same children in grades three and four and a sample of adult readers (Tiffin-Richards & Schroeder, 2018). Parker, Slattery, et al. (2019) reported no difference between accurate line-initial and intra-line fixations in children reading silently. However, Chapter 4 provided the first evidence that this is not the case for oral reading. Accurate line-initial fixations were significantly longer than intra-line fixations for all grades.

Overall, I suggest that these findings were due to the greater need to coordinate the eye and the voice at line boundaries. To evaluate this hypothesis and answer the crucial question of this chapter, interaction effects between fixation types and EVS were examined. I report for the first time that the EVS impacts fixations adjacent to the return-sweep much more than intra-line fixations as predicted. Specifically, the EVS effect on line-final and undersweep fixations was more substantial than the EVS effect on intra-line fixations. However, the EVS effect on accurate line-initial and intra-line fixations were similar. These findings were interpreted as higher-level cognitive processing demands interrupting fixations which are more involved with oculomotor planning processes. Other EVS effects at line boundaries were reported; the EVS at the end of the previous line also impacted landing positions and corrective saccades. Larger EVSs at the end of the line-final fixation were associated with leftward landing positions and fewer

corrective saccades for launch positions closer to the left margin. The landing position finding suggests that developing readers were able to use the return-sweep to modulate the EVS when they could take advantage of visual acuity benefits. Fewer corrective saccades were interpreted as resulting from leftward landing positions.

7.1.4. Chapter 5: Reliability and Individual Differences in the Eye-voice Span and its Modulation

In Chapter 5, I explored the reliability of the EVS during sentence reading which is a novel contribution to existing literature. To our knowledge, the only report of an EVS estimate in the literature was in a RAN task (0.88; Gordon & Hoedemaker, 2016). RAN tasks are related to reading however, the RAN task is different from reading as RAN does not require lexical, syntactic, or semantic processes. This study employed two ways of calculating the spatial EVS, either from fixation or articulation onset. The articulation onset measure produced a higher reliability estimate of 0.77. On the other hand, the reliability estimate of the temporal onset EVS (time lag between a word's fixation and articulation onset) was much higher at 0.92. Furthermore, I examined individual differences in the EVS using offline measures of reading-related skills. These analyses revealed that word reading efficiency, vocabulary, and RAN speed predicted a reader's EVS. In addition, spelling ability predicted how variable a reader's EVS was. There was a clear differential effect of spelling and word reading on gaze duration and saccade length respectively. Word reading efficiency predicted gaze duration while only spelling predicted saccade length. The spelling effect was consistent with previous literature on skilled reading Crucially, the offline measures jointly accounted for greater variability in the EVS than they accounted for in the gaze duration measure. These findings suggest that the EVS is a multifaceted construct that captures more about the reading process than eye movements alone, at least for children who primarily read aloud.

7.1.5. Chapter 6: Bi-directional Lexical influences during Oral Reading

The final chapter in this thesis examined the interactions between articulation and gaze during oral reading. I did this by investigating whether the frequency and length of the word a reader utters impact how long they look at the concurrently fixated word (speech load effect). Similarly, I investigated whether the frequency and length of the word a reader looks at impacts how long it takes to utter the concurrently articulated word (foveal load effect). While frequency effects during word recognition are well established, frequency effects on articulation duration are equivocal. Therefore, I examined in our

dataset whether frequency effects were present for articulation duration. Our findings confirmed this and provided evidence for speech load influences on gaze duration while the reverse (i.e., foveal load effect on articulation duration) was largely absent. I interpreted these findings in the context of dual-task performance costs, where limited attentional capacity results in sharing attention when the lexical load of the articulated word is high (low frequency and long words) compared to when it is low (high frequency and short words). These findings suggest for the first time that word properties of the articulated word impact eye movements in addition to other factors such as eye-voice coordination, as shown in Chapter 4.

7.2. Theoretical and Methodological Implications

7.2.1. The eye voice span during oral reading

Oral reading is similar to silent reading, except that oral reading requires the overt pronunciation of words (Juel & Holmes, 1981). This additional requirement results in lower oral reading rates compared to silent reading rates (Brysbaert, 2019). Local changes in eye movements also occur due to slow speech processes namely, fixations are longer and more frequent, and saccades are shorter (Adedeji et al., 2021; Anderson & Swanson, 1937; Krieber et al., 2016). In chapter 2, this evidence was replicated in skilled passage reading. Primarily, such changes in eye movement behaviour have been associated with the coordination of the eye and the voice (Kim et al., 2019; Laubrock & Kliegl, 2015; Vorstius et al., 2014). In Chapters 4, 5 and 6, I present this evidence in a sample of developing readers for the first time. Chapter 4 pointed to the direct effects of the EVS on fixation durations: larger EVSs resulted in longer fixation durations. Chapter 5 showed that this effect is dependent on a reader's skill; the EVS effect on fixation durations was greater for readers with lower word reading efficiency scores. Meanwhile, Chapter 6 reported evidence that articulated word properties such as word length and frequency could impact fixation durations of the concurrently fixated word in cases where the EVS was at least one word.

Models of eye movement during reading currently account for silent reading and not oral reading behaviour. At the heart of linguistic models is the assumption that written language proficiency drives eye movements rather than eye movements determining language processing. Two key assumptions of the E-Z reader model described in the introduction are that: *(i)* attention is allocated to words serially, and *(ii)* attention shifting

and saccade programming are independently executed. Oral reading provides an excellent opportunity to assess the extent of attention allocation during reading. Previous studies have shown that parafoveal information processing and the perceptual span are reduced during oral reading (Ashby et al., 2012; Pan et al., 2016). Perceptual span effects during oral reading are attributed to a decrease in attentional resources due to additional coordinative demands and articulatory processes (Pan et al., 2017). The studies presented in this thesis suggest that eye-voice coordination (Chapters 4 and 5) and interference from articulated word properties (Chapter 6) may account for such perceptual span and overall eye movement differences between oral and silent reading by constraining shifts of attention.

The conception of the EVS as an online working memory buffer operating during oral reading provides a sound framework for understanding the implication of these findings (Baddeley & Hitch, 1974; Laubrock & Kliegl, 2015). According to this account, phonological representations of words are stored in the working memory buffer for later articulation. However, when these representations become more than what the limited working memory capacity can hold, the oculomotor system "puts the brakes on", similar to what happens during post-lexical integration failures (Reichle et al., 2009). Therefore, while coordinative and additional task requirements cause delays in attention shifting, the modulating EVS effect on fixation durations suggests that working memory demands also influence such delays. Perhaps, the effect of the EVS on fixation durations could be interpreted within a joint attention and working memory framework, whereby the more representational units in working memory, the greater the depletion of attentional resources (Cowan, 1998). Considering the E-Z reader model, it is possible that the size of the EVS modulates attention shifting as attention that should have been allocated earlier to word N+1 is delayed when the EVS is large compared to when it is small. In such instances, little time intervenes between the completion of L2 and initiation of a saccade program to the next word leading to smaller preview benefits as modelled by the E-Z reader model. However, in its current form, the E-Z reader model cannot account for such effects and modelling work is required to ascertain the specific stages of lexical and/or oculomotor processing the EVS impacts.

Like the E-Z reader model, the SWIFT model of eye movement behaviour also assumes that linguistic processes drive eye movement behaviour. Foveal difficulty is assumed to inhibit eye movements generated autonomously by a random timer. This occurs when the foveal word is of low frequency. However, one key difference between both models, is whether or not words are processed serially. The SWIFT model proposes

that words in the perceptual span are processed in parallel. The attention allocated to words is usually also dependent on foveal difficulty, i.e., fixated words of low frequency reduce the perceptual span and leaves fewer words to be processed in parallel. In its current form the SWIFT model does not account for eye movement differences between oral and silent reading and does not take the dynamics of EVS modulation on eye movement behaviour into account. Based on the findings from this body of work, several suggestions can be made regarding how this might be possible. First, a general slowing of autonomous random timer due to additional articulatory processes could account for longer fixation durations (Laubrock et al., 2006). However, this mechanism would to increase skipping as parafoveal processing should be greater when fixation durations are longer. With evidence for less skipping in oral reading (Laubrock & Kliegl; 2015;Vorstius et al., 2014), this modification is less plausible. In addition, modification of this mechanism would not explain the variation in fixation durations due to variations in the EVS as found in Chapter 4. Therefore, an alternative mechanism that could be modified is that foveal difficulty may be increased when EVS is larger (Chapter 4) and articulated word is of lower frequency (Chapter 6). In this situation, lexical activation of words in the perceptual span would not only depend on word frequency but on the EVS and properties of the articulated word. Such modifications would account for reduced perceptual span, longer fixation durations and less skipping. Again, like the E-Z reader, further research and modelling work need to be done.

One methodological benefit of an oral reading paradigm is the acquisition of measures which strongly reflect a child's reading proficiency (Kim et al., 2019). Additionally, for children whose reading is error-prone, an oral reading experiment allows experimenters to exclude incorrectly pronounced words (Marx et al., 2015; Rau et al., 2015). Oral reading also allows children who perhaps are more prone to mind wandering to engage fully with each word in the text (Fuchs & Maxwell, 1988; Miller & Smith, 1985; Molina et al., 2020), producing reliable eye movement data as found in Chapter 5. Multiple measures provide a clearer meaning of a construct (Kagan et al., 2002). An oral reading paradigm complemented with eye-tracking permits the measurement of speech related and eye-movement measures. Importantly, the EVS is a combination of measurements from both domains. In Chapter 5, I show that the EVS may reflect more about the reading process and offer an online indicator of the reading process. This evidence is in line with research discriminating readers with dyslexia from typical readers based on the size of the EVS during RAN and reading tasks (De Luca et al., 2013; Jones et al., 2008; Pan et al., 2013). I also dissociated the relevance and applicability of

two broad EVS measures. Although the temporal EVS measure was of excellent reliability, the spatial EVS was predicted by most reading-related skills. Recent research has shown the absence of developmental differences in spatial EVS across grades two (7 years), four (9 years), seven/ eight (13 years) and adults during RAN tasks (Easson et al., 2020). This finding is difficult to reconcile with the earliest EVS research (Buswell, 1920) and available evidence in chapter 3. In Chapter 3, spatial EVS differences were found in grades 4 and 5. Easson et al. (2020) found developmental differences in the temporal onset EVS across the four groups, contrasting with the individual difference evidence on temporal onset EVS in chapter 5. Differences between Easson et al. (2020) and the evidence in chapters 3 and 5 could be related to task differences. RAN and oral reading are related because they share similar processes of attention to stimuli, visual processing, orthographic to phonological mapping, phonological retrieval, conceptual integration, and speech motor activation (Norton & Wolf, 2012). However, more than these, oral reading requires higher-level semantic and syntactic integration processes that are reflected in changing prosody across texts (Kuhn et al., 2010; Miller & Schwanenflugel, 2008). Such prosodic features of oral reading reflect comprehension skills that may be captured in sentence reading but not the RAN task with EVS measures. While this account is attractive, the Easson et al. (2020) study revealed group-by-task (objects versus letters) interactions where a larger task effect was found for older readers compared to younger readers. Essentially, no developmental differences in spatial EVS were found for object naming but a trend was observed for letter naming. Regardless of the difference between our study and Easson et al (2020), it appears that the spatial EVS is more sensitive to reading skill differences in developing readers compared to the temporal EVS. This is also confirmed by the Easson et al., study where no difference in temporal EVS was found between children in grades two and four. While it is possible that the temporal EVS captures some other aspects of cognitive processing not directly tested here, the spatial EVS can be regarded as a robust metric for future EVS developmental research.

7.2.2. The eye-voice span and return-sweep saccades

Return-sweep saccades have mainly been studied in the context of silent reading research. Oral reading studies examining return-sweeps have not made a comparison with silent reading (Molina et al., 2020; Trauzettel-Klosinski et al., 2010). In Chapter 2, the fixations adjacent to the return-sweep saccade (line-final and accurate line-initial fixations) were affected more by oral reading compared to intra-line fixations during skilled adult reading. This oral reading cost was further confirmed in the developmental study in

Chapter 4. Previous research reported that children aged 6 to 9 years showed a similar decrease in line-final fixations compared to adults during silent reading (Parker, Slattery, et al., 2019). However, the line-final speed-up effect found in children's oral reading was of limited practical significant (Cohen's d- 0.03) and only significant for children in grade five compared to children in grades three and four. In addition, all the children showed significantly greater accurate line-initial fixations compared to intra-line fixations in contrast to what has been found in silent reading (Parker, Slattery, et al., 2019). These findings show how an additional articulatory requirement can interfere with developing readers' oculomotor planning and linguistic processes. This is because line-final fixations are thought to be responsible for return-sweep planning and foveal processing at the end of the line (Parker & Slattery, 2021). Further analysis in Chapter 4 also confirmed that the increased costs at line boundaries could be due to the EVS coordination. A greater effect of the EVS on fixations at line boundaries, i.e., line-final and undersweep fixations, was reported. Linking these findings to the preceding section, I suggest that the oculomotor system *puts the breaks on* for line-final fixations to ensure optimal lexical processing is completed, and the voice catches up considerably to avoid a costly regression back to the previous line.

Again, in Chapter 4, oral reading and the EVS impacted eye movement patterns around line-boundaries comprising of line-final fixations, accurate line-initial fixations, and undersweep fixations. Specifically, children in grades 3 and 4 did not show line-final speed-up effects, while all children showed longer accurate line-initial fixations compared to intra-line fixations. Similarly, the EVS impacted line-final and undersweep fixations more than intra-line fixations. These findings show that the fixations around the return-sweep are crucial in aiding our understanding of higher-level cognitive influences on eye movements. More importantly, these fixations may increase overall reading times. For example, Molina et al. (2020) found that the frequency of corrective saccades was moderately related to the time spent reading text. When fixations around return-sweeps are excluded by eliminating line-final, and line-initial words (Portillo, 2020; Vorstius et al., 2014; Whitford & Joanisse, 2018), how these fixations contribute to global reading measures may be masked. Importantly, it was observed that the line-final speed-up effect between grades three, four and five was parallel to the observed age-equivalent sight word efficiency scores, gaze durations, spatial EVS and articulation durations differences across these grades (see Table 3.1). That is, the same way no differences were found in these measures between grades three and four is the same way no differences were found for the line-final speed-up effects for the two groups. This suggests that the line-final

fixation duration during oral reading is perhaps an informative eye movement metric for understanding reading development. In relation to this, Gordon and Hoedemaker (2016) found that participants with a larger EVS were more likely to spend less time completing RAN items than participants with smaller EVS. Interestingly this relationship was much stronger for RAN items around line boundaries compared to central items suggesting that EVS coordination is crucial around line breaks (Gordon & Hoedemaker, 2016). Altogether, these findings show that documenting the nature of fixations adjacent to return-sweep saccades during oral reading and how the EVS impacts them have methodological benefits for research and potentially assessment benefits for identifying struggling readers. That is, fixations around return-sweeps may give additional information about differences in reading abilities compared to intra-line fixations alone.

7.3. Developmental Implications

The primary difference between the eye movements of skilled readers and developing readers is their rate of lexical and language processing (Leinenger et al., 2017; Mancheva et al., 2015; Reichle et al., 2013). The results reported in this thesis are largely compatible with this proposition. These results are equally consistent with the evidence showing that eye movements of adult readers and first graders matched on word reading skills are remarkably similar (Barnes & Kim, 2016). In Chapters 3 to 6 of this thesis, the eye movement and voice data of developing readers in grades three, four and five were analysed to explore several aspects of online reading behaviour. Expected gaze duration differences between grades three and four were absent. This pattern was echoed in an analysis of offline reading-related measures, where both grades did not differ in their sight word efficiency scores. However, the eye movement difference in gaze duration was compatible with the word reading efficiency scores for grades four and five. Therefore, reiterate what has been found in previous research, that eye movement behaviour during reading is more strongly related to linguistic proficiency than age-related oculomotor control or visual processing skills (Blythe et al., 2009; Huestegge et al., 2009; Reichle et al., 2013).

Interestingly, this developmental pattern extended beyond eye movement measures. Similar grade differences were also reported for articulation duration and spatial EVS, suggesting a close link between linguistic proficiency and speech fluency (Catts, 1986; Popescu & Noiray, 2021; Saletta et al., 2016). Popescu and Noiray (2021) reported a lower degree of coarticulation in better readers than poor readers in the first grade.

Similarly, Saletta et al. (2016) found that adults' decoding and comprehension skills predicted speech motor stability, assessed by the degree of variability in the coordination between upper and lower lips during nonword production. Traditional theories of speech production propose a distinction between higher-level language processing and lower-level motor skills, emphasising one over the other (Barlow et al., 2010; Levelt et al., 1999; Saletta et al., 2015). However, some theorists argue for an interactive model between linguistic and motor processing (see Rapp & Goldrick, 2006). Our findings support such interactive models. More evidence of this comes from Chapter 3, where a high-level coordinative process as indexed by the EVS impacted articulation rates. In addition, Chapter 6 revealed frequency effects on articulation duration, suggesting more of a cascaded rather than a staged view of speech production during reading aloud.

Oral reading presents a natural medium through which children's online reading behaviour can be studied because it is how they first learn to read (Rasinski & Hoffman, 2003; Rayner et al., 2013). Beginning readers link printed words to their well-established oral language repertoire through oral reading by activating pre-existing connections between letters in spelling and sounds in pronunciation. This concept of making connections, called orthographic mapping, has been explained by Ehri (2017). In her overlapping phase model of reading development, the nature of connections changes as children acquire more skills and experience with words. While the nature of letter-sound connections, characteristic of the full alphabetic phase has been well studied through behavioural methods and eye movements, less is known about the trajectory of the consolidated alphabetic stage where grapho-syllabic connections are predominant. At this stage, words are read by activating pre-existing syllabic constituents rather than individual letters. In Chapter 3, I examined the trajectory of syllabic connections during oral reading, knowing that syllables are representational units in spoken language. Children in our sample, aged 7 to 10 years in grades three, four and five, usually fall within this syllabic or consolidated alphabetic stage (Bhattacharya & Ehri, 2004). However, I found that our readers processed one-syllable words more slowly than two-syllable words, as reflected in their gaze duration. Several interpretations could be provided for this pattern. I envisage that this result may be due to the stimuli list used (see Challenges and Future Research Directions) and propose that developing readers may be sensitive to sub-syllabic structures such as onset and rimes (Treiman, 1985, 1991; Treiman et al., 1995). The complexity of an onset such as consonant structure might influence word processing time. Almost all one-syllable target words had consonant clusters, while most two-syllable words had single consonants. Ehri's model specifies

that children at this stage, can make use of other letter grouping and sound connections such as onset and rimes and morphemes (Ehri, 2005a). Therefore, our findings could still be assumed to provide evidence for the consolidated alphabetic stage.

7.4. Challenges and Future Research Directions

While this body of work presents several additions to eye movement research at the theoretical, methodological and developmental levels, it is not without potential limitations. The main limitation of this work was in the design, which was ideally to investigate longitudinal changes in children's eye movement behaviour and EVS across two-time points. However, due to covid-19 restrictions, this was impossible. Notwithstanding, a cross-sectional comparison in Chapter 3 and a closer look at individual differences in Chapter 5 yielded benefits. Although a related issue was the sample size, I observed how groups of children with different ages but similar average word reading skills exhibited no statistical differences between all dependent measures in experiment 2. This group comparison amplified the importance of linguistic proficiency hypothesis in driving eye movements beyond oculomotor development.

For individual differences studies to be generalisable, a large sample is required. However, considering the limitations of carrying out EVS research with regard to the laborious process of manual segmentation of audio recordings, as mentioned in Chapter 5, such research will be costly and require more time and resources. Therefore, it was essential to highlight the potential benefits of measuring the EVS as it relates to current debates in eye movements and reading development in a limited sample before such an onerous task is embarked on. Additionally, the analysis and results presented throughout this thesis justify the call for researchers to invest resources in developing automated methods of audio segmentation and EVS calculation.

One key aspect of this research was the experimental manipulation in the second experiment assessing the effect of syllable number. One reason our findings may diverge from current evidence lies in the initial phoneme of the stimuli. Initial phoneme characteristics have been found to influence naming latencies in behavioural research, particularly when the voice key is used rather than manual segmentation as used in this thesis (Rastle & Davis, 2002). Nevertheless, one study by Balota et al. (2004) showed that the voicing characteristic of the initial phoneme influenced not only naming latency but also lexical decision. Therefore, one way this confound could have been averted was by matching the one and two syllables words with the same initial phoneme. Jared and

Seidenberg (1990) did this and found inhibitory effects of syllable number where two-syllable words took longer to begin naming compared to one-syllable words in skilled readers. Although the fact the number of phonemes was not controlled also confounds this finding. Nevertheless, one issue with developing stimuli for experimental psycholinguistic research with children is the limited amount of words within a child's vocabulary. This makes it difficult to perfectly match conditions on different variables. Our unique design also ensured that one and two-syllable words fit within two different sentence frames. While these limitations are apparent, it does not reduce the quality and potential contribution of the results from this thesis. EVS research is relatively scarce, so the current work lays a solid foundation for subsequent research in the field.

Throughout this thesis, working memory was consistently linked with the EVS. However, no study has examined whether a reader's working memory capacity is related to their EVS. Examining this relationship is essential to draw firm conclusions on the conceptualisation of the EVS as an online working memory buffer during oral sentence reading (Buswell, 1920; Laubrock & Kliegl, 2015). A similar analogy was made in ear-voice span research during simultaneous interpreting (Gile, 1999). However, associating the ear-voice span with working memory capacity yielded null results (Collard & Defrancq, 2018). Therefore, future work should consider how working memory capacity may be related to the EVS. Additionally, in this thesis, I referred to the EVS as reflecting reading processes. Reading is the ability to decode words and comprehend those words. Therefore, to understand the diagnostic value of the EVS fully, its relationship to measures of comprehension beyond other code and language-related skills examined in this thesis is necessary.

Finally, the analysis of return-sweep saccade in children's oral reading lacked a baseline of silent reading for comparison. This baseline would have enabled us to substantiate the claim that reading aloud is indeed more costly at line boundaries and that the observed return-sweep effects are not due to our specific sample. However, it is clear from previous research and the different studies presented in this thesis that our claim is indeed credible.

7.5. Concluding Remarks

A growing number of developmental eye movement reading researchers have used the oral reading paradigm (Hyona & Olson, 1995; Kim et al., 2019, 2020; Krieber et al., 2016; Krieber et al., 2017; Marx et al., 2015; Vorstius et al., 2014). Only a few researchers

have studied return-sweep saccades in developing readers (Molina et al., 2020; Parker et al., 2020; Parker, Slattery, et al., 2019; Trauzettel-Klosinski et al., 2010). This thesis presents the first developmental and systematic description of the EVS during English multi-line passage reading using modern eye-tracking equipment and high-level statistical analyses. I also document how this EVS measure impacts children's eye movements. What is clear from this thesis is that attentional resources are depleted during oral reading due to additional articulatory demands and the coordination of the EVS. For developing readers, return-sweep saccades appear to be more impacted by this coordination compared to intra-line saccades. By documenting the reliability and validity of the EVS in relation to other reading-related skills, it is hoped that this body of work can guide future researchers in formulating questions that probe into the nature of the interaction between oculomotor, speech-motor, and linguistic processes during reading development.

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APPENDIX A

Passage Stimuli used in Chapters 3 to 5. The target words for each passage are formatted in bold font. Odd numbered items have the one-syllable words embedded while the two-syllable words are embedded in the even numbered items. Items 1-42 were part of Set 1 and items 43-84 were part of Set 2. Each syllable condition was embedded in one of two sentence frames. Hence, the repeated numbering indicates the alternative sentence frame with the same target word.

1	A huge bowl of **spoilt** fruit was on the table. It must have been there for days.
1	John could not stand the **spoilt** cheese left on the shelf. He threw it in the outside bin.
2	John could not stand the **smelly** cheese left on the shelf. He threw it in the outside bin.
2	A huge bowl of **smelly** fruit was on the table. It must have been there for days.
3	I found a piece of **thread** in my pocket. The wind blew it away as I took it out.
3	She rolled out some **thread** until she had enough. She would need it for her sewing class.
4	She rolled out some **tissue** until she had enough. She would need it for her sewing class.
4	I found a piece of **tissue** in my pocket. The wind blew it away as I took it out.
5	The bird landed on the **branch** and rested there. Ed ran towards it and it flew away.
5	He held tightly to the **branch** because he was scared. He had always been afraid of heights.
6	He held tightly to the **ladder** because he was scared. He had always been afraid of heights.
6	The bird landed on the **ladder** and rested there. Ed ran towards it and it flew away.
7	Katie went past the **bridge** on her way to school. It was the best part of the ride.
7	The police looked near the **bridge** for the missing sisters. They had been lost for a week.
8	The police looked near the **castle** for the missing sisters. They had been lost for a week.
8	Katie went past the **castle** on her way to school. It was the best part of the ride.
9	The boy was asked to draw a **square** in his book. He coloured it brown and black.
9	He could tell which **square** was the smallest on the picture. It was the one at the left corner.
10	He could tell which **donkey** was the smallest on the picture. It was the one at the left corner.
10	The boy was asked to draw a **donkey** in his book. He

	coloured it brown and black.
11	Henry looked at the **screen** for a few minutes. He was starting to daydream.
11	Abby got a good price for the **screen** she sold on Friday. But it was hard to find a buyer.
12	Abby got a good price for the **mirror** she sold on Friday. But it was hard to find a buyer.
12	Henry looked at the **mirror** for a few minutes. He was starting to daydream.
13	Tom thought the warm **breeze** was wonderful. It took his mind off his worries.
13	The nice **breeze** helped to cheer Sally up. It also made her relax and ready for the show.
14	The nice **cuddle** helped to cheer Sally up. It also made her relax and ready for the show.
14	Tom thought the warm **cuddle** was wonderful. It took his mind off his worries.
15	Sandra put her **brooch** away when she got home. She always kept it in a special case.
15	Bella grabbed the **brooch** quickly and hid it. She did not want her cousin to find it.
16	Bella grabbed the **fiddle** quickly and hid it. She did not want her cousin to find it.
16	Sandra put her **fiddle** away when she got home. She always kept it in a special case.
17	I told Chris that my favourite **squash** could be bought at the store. He seemed to like it too.
17	Amy always had **squash** for breakfast. It was quick to make and the doctor said it was good for her.
18	Amy always had **cereal** for breakfast. It was quick to make and the doctor said it was good for her.
18	I told Chris that my favourite **cereal** could be bought at the store. He seemed to like it too.
19	James found a **prince** costume and tried it on. He played with Emily who dressed as a princess.
19	The King did not invite the **prince** to the great feast. This made him very upset and lonely.
20	The King did not invite the **wizard** to the great feast. This made him very upset and lonely.
20	James found a wizard **costume** and tried it on. He played with Emily who dressed as a princess.
21	Meg began to **scream** as she jumped into the cold water. When she got out, she sat near the campfire.
21	I always **scream** whenever I see clowns. They are really scary to look at.
22	I always **shiver** whenever I see clowns. They are really scary to look at.
22	Meg began to **shiver** as she jumped into the cold water. When she got out, she sat near the campfire.
23	The man rushed to the **ground** floor to escape the fire. His family was hoping he would make it.

23	He moved from the **ground** to the top of the building with the stairs. This made him very tired.
24	He moved from the **bottom** to the top of the building with the stairs. This made him very tired.
24	The man rushed to the **bottom** floor to escape the fire. His family was hoping he would make it.
25	She wanted a pink **blouse** because it was her favourite colour. Her sister wanted the same too.
25	Laura's new **blouse** was very nice and soft. It was made of thick and fluffy wool.
26	Laura's new **pillow** was very nice and soft. It was made of thick and fluffy wool.
26	She wanted a pink **pillow** because it was her favourite colour. Her sister wanted the same too.
27	Oscar sat on the **bright** chair in his bedroom. He read a book as he sipped a cup of tea.
27	The classroom was filled with **bright** desks and chairs. The students liked them very much.
28	The classroom was filled with **wooden** desks and chairs. The students liked them very much.
28	Oscar sat on the **wooden** chair in his bedroom. He read a book as he sipped a cup of tea.
29	Billy thought the **strong** wrestler would surely win. Sadly, he lost at the start of the match.
29	The hikers used the **strong** rope to climb down the cliff. They slipped down very slowly.
30	The hikers used the **bigger** rope to climb down the cliff. They slipped down very slowly.
30	Billy thought the **bigger** wrestler would surely win. Sadly, he lost at the start of the match.
31	Sara loved the summer **warmth** in Spain. She spent most days on the beach.
31	The new **warmth** brought flower blossoms. They filled the fields with beautiful colours.
32	The new **season** brought flower blossoms. They filled the fields with beautiful colours.
32	Sara loved the summer **season** in Spain. She spent most days on the beach.
33	She was startled by the **sneeze** that came from the crowd. This made her feel nervous.
33	The loud **sneeze** woke the baby. Anna rushed in when she heard him crying.
34	The loud **rustle** woke the baby. Anna rushed in when she heard him crying.
34	She was startled by the **rustle** that came from the crowd. This made her feel nervous.
35	The men will **spread** the news of Leo's arrest to everyone. He was a well-known robber.
35	The women did not **spread** their secrets to anyone. They could not bear the shame.
36	The women did not **reveal** their secrets to anyone.

	They could not bear the shame.
36	The men will **reveal** the news of Leo's arrest to everyone. He was a well-known robber.
37	Betty had a quick **snooze** to get herself ready for the test. She scored very well on it.
37	I had a little **snooze** before I went out for lunch. Troy was already waiting for me.
38	I had a little **lesson** before I went out for lunch. Troy was already waiting for me.
38	Betty had a quick **lesson** to get herself ready for the test. She scored very well on it.
39	I put my shirt in the dryer, and it **shrank** so small I could not wear it. I could not believe it.
39	The boy used magic and **shrank** the tall ninja from the film he had seen. Too bad it was only a dream.
40	The boy used magic and **became** the tall ninja from the film he had seen. Too bad it was only a dream.
40	I put my shirt in the dryer, and it so small I could not wear it. I could **became** not believe it.
41	My 6 a.m. **flight** was very long and tiring. I arrived almost a day later.
41	It is time to begin my **flight** across the world to visit my family. I cannot wait to see them.
42	It is time to begin my **voyage** across the world to visit my family. I cannot wait to see them.
42	My 6 a.m. **voyage** was very long and tiring. I arrived almost a day later.
43	Bill found a **smooth** pebble at the beach. He put it in his pocket to show his mum later.
43	Ella poured some juice into **smooth** glasses for her friends. They all enjoyed it with their snack.
44	Ella poured some juice into **purple** glasses for her friends. They all enjoyed it with their snack.
44	Bill found a **purple** pebble at the beach. He put it in his pocket to show his mum later.
45	Mum had put some water in the **fridge** to use later. She would like a drink with her meal.
45	The brand-new **fridge** was grey and shiny. It was a wedding gift from my uncle.
46	The brand-new **kettle** was grey and shiny. It was a wedding gift from my uncle.
46	Mum had put some water in the **kettle** to use later. She would like a drink with her meal.
47	Will's mum thought the **priest** was very nice. She met him at the town centre last weekend.
47	The famous **priest** made them happy. They all wanted a picture with him.
48	The famous **singer** made them happy. They all wanted a picture with him.
48	Will's mum thought the **singer** was very nice. She met him at the town centre last weekend.

49	The soldiers lost the **chance** to their enemies. It was a sad day for them.
49	He saw life as a **chance** and made the best of it. He always fought for what was his.
50	He saw life as a **battle** and made the best of it. He always fought for what was his.
50	The soldiers lost the **battle** to their enemies. It was a sad day for them.
51	Bob was happy the **cruise** had many fun activities. He had a good time with his two friends.
51	Ray wished the **cruise** had many games. He got bored too easily and wanted to go home.
52	Ray wished the **arcade** had many games. He got bored too easily and wanted to go home.
52	Bob was happy the **arcade** had many fun activities. He had a good time with his two friends.
53	Dad would need a **sponge** to clean the mess. Buffy spilled his dog food everywhere.
53	Barry put the **sponge** under the tap. Then he added some soap to do some washing.
54	Barry put the **bucket** under the tap. Then he added some soap to do some washing.
54	Dad would need a **bucket** to clean the mess. Buffy spilled his dog food everywhere.
55	Gary found his **sledge** handy at winter time. He had thought he could not use it again.
55	The plastic **sledge** still has its price tag on. It was given to my Aunt ten years ago.
56	The plastic **bottle** still has its price tag on. It was given to my Aunt ten years ago.
56	Gary found his **bottle** handy at winter time. He had thought he could not use it again.
57	Jill fixed the **sleeve** of her new dress. She wanted to wear it for a party.
57	A butterfly landed on the **sleeve** of Mary's dress. She stood still so it would not fly away.
58	A butterfly landed on the **buckle** of Mary's dress. She stood still so it would not fly away.
58	Jill fixed the **buckle** of her new dress. She wanted to wear it for a party.
59	Oliver heard a **squeak** as he moved along the hall. He turned back to find out which room it came from.
59	It was hard to notice the **squeak** inside the engine. He came closer so he could hear it.
60	It was hard to notice the **tinkle** inside the engine. He came closer so he could hear it.
60	Oliver heard a **tinkle** as he moved along the hall. He turned back to find out which room it came from.
61	Mum made a tasty **shrimp** dish for her guests. I had to try some of it before they came.
61	Wayne and I ordered **shrimp** and potato soup for

	lunch. We had some sandwiches with it.
62	Wayne and I ordered **carrot** and potato soup for lunch. We had some sandwiches with it.
62	Mum made a tasty **carrot** dish for her guests. I had to try some of it before they came.
63	I saw my **friend** waiting at the gate of the park. He was waving so I could spot him easily.
63	Today is a special day for my **friend** since it is his birthday. We will have some chocolate cake.
64	Today is a special day for my **father** since it is his birthday. We will have some chocolate cake.
64	I saw my **father** waiting at the gate of the park. He was waving so I could spot him easily.
65	I wanted to check the **length** of the snake but I was too scared. It was so long!
65	I was shocked by the **length** of the picture on the wall. It looked like a snail was hiding behind it.
66	I was shocked by the **shadow** of the picture on the wall. It looked like a snail was hiding behind it.
66	I wanted to check the **shadow** of the snake but I was too scared. It was so long!
67	I felt hungry so I ate some **French** bread as a snack. I bought it from the bakery next door.
67	Liz speaks **French** with her parents at home. But she talks to friends and teachers in English.
68	Liz speaks **Danish** with her parents at home. But she talks to friends and teachers in English.
68	I felt hungry so I ate some **Danish** bread as a snack. I bought it from the bakery next door.
69	Jack thought he would **starve** before lunch was served. He spent all morning playing football.
69	His mum knew he would not **starve** before the roast was done. He was having too much fun outside.
70	His mum knew he would not **arrive** before the roast was done. He was having too much fun outside.
70	Jack thought he would **arrive** before lunch was served. He spent all morning playing football.
71	His grandma used a **stitch** to fix the hole in his red shirt. It was a very old shirt.
71	The artist used the **stitch** to hold the cloth together. It was the best he could do.
72	The artist used the **needle** to hold the cloth together. It was the best he could do.
72	His grandma used a **needle** to fix the hole in his red shirt. It was a very old shirt.
73	Tim tried to stand up in the **stream** but fell over. His friend, Max helped him up.
73	Sam spent the day fishing in the **stream** with his grandpa. He was glad to have caught so many fish.
74	Sam spent the day fishing in the **dinghy** with his grandpa. He was glad to have caught so many fish.

74	Tim tried to stand up in the **dinghy** but fell over. His friend, Max helped him up.
75	There was broken glass in the **street** after the crash. It was cleared up so no one would get hurt.
75	The Christmas lights used to decorate the **street** were red and green. They were lovely to look at.
76	The Christmas lights used to decorate the **window** were red and green. They were lovely to look at.
76	There was broken glass in the **window** after the crash. It was cleared up so no one would get hurt.
77	The car had a cool **stripe** on the driver's side. It was one of the newest cars in town.
77	Joe's t-shirt had a blue **stripe** on the left sleeve. It was almost the same as Todd's shirt.
78	Joe's t-shirt had a blue **design** on the left sleeve. It was almost the same as Todd's shirt.
78	The car had a cool **design** on the driver's side. It was one of the newest cars in town.
79	The children loved the **throne** they saw at the museum. They had never seen anything like it.
79	They took a picture of the **throne** when they went to the palace. They moved close to get a good shot.
80	They took a picture of the **armour** when they went to the palace. They moved close to get a good shot.
80	The children loved the **armour** they saw at the museum. They had never seen anything like it.
81	Good books were **scarce** when I was a child. The man at the library tried to get as many as he could.
81	White horses are **scarce** in this town. It is quite different where I come from.
82	White horses are **normal** in this town. It is quite different where I come from.
82	Good books were **normal** when I was a child. The man at the library tried to get as many as he could.
83	John had to wipe the **grease** from his hands after eating so much pie. The pie was blueberry flavour.
83	There was a **grease** stain on my white trousers. It was hard to remove later.
84	There was a **cherry** stain on my white trousers. It was hard to remove later.
84	John had to wipe the **cherry** from his hands after eating so much pie. The pie was blueberry flavour.

APPENDIX B

Chapter 3 Supplementary Material

LMM analysis of untransformed gaze and articulation durations

Table B1. LMM Analyses Showing Untransformed Gaze duration as a Function of Grade and Number of syllables

Fixed effects	*b*	*SE*	*t*	*p*
Intercept	507.578	25.369	20.008	<0.01
Syllable number	*30.573*	*15.566*	*1.964*	*0.054*
Grade 3-4	26.109	54.172	0.482	0.632
Grade 4-5	-210.452	50.071	-4.203	**<0.01**
Word Frequency	*-30.74*	*15.78*	*-1.948*	*0.056*
AoA	81.216	15.592	5.209	**<0.01**
Syllable number * Grade 3-4	4.464	21.477	0.208	0.835
Syllable number * Grade 4-5	-21.143	19.679	-1.074	0.283
Random effects	Var.	SD		
Item intercept	12986	114		
Subject intercept	19821	140		
Residual	115480	340		

Table B2. LMM Analyses Showing Untransformed Articulation duration as a Function of Grade and Number of syllables

Fixed effects	*b*	*SE*	*t*	*p*
Intercept	607.231	25.607	23.714	<0.01
Syllable number	7.772	12.982	0.599	0.551
Grade 3-4	6.794	31.023	0.219	0.828
Grade 4-5	-103.239	28.667	-3.601	**0.001**
Word Frequency	-6.196	10.002	-0.619	0.538
AoA	52.097	9.797	5.318	**<0.01**
Phonological Neighbourhood size	-8.112	9.683	-0.838	0.405
Initial phoneme voicing	-56.381	21.679	-2.601	**0.011**
Final phoneme voicing	-19.923	24.833	-0.802	0.425
Syllable number * Grade 3-4	1.566	14.717	0.106	0.916
Syllable number * Grade 4-5	-16.532	13.557	-1.219	0.229
Random effects	Var.	SD		
Item intercept	5770	76		
Subject intercept	6914	83		
Residual	24881	158		

LMM analysis of offline measures and syllable number on gaze duration

Since grades three and four children did not significantly differ in the eye movement and reading ability measures as indicated by their age-equivalent sight word efficiency scores, we explored whether individual differences might modulate the syllable number effect for all children. Therefore, we replaced grade with each of the individual difference measure that related to reading and language proficiency and ran separate LMMs. The results for gaze duration are presented in the following tables:

Table B3. LMM Analyses Showing Gaze duration as a Function of TOWRE-Total word reading efficiency score and Number of syllables

Fixed effects	*b*	*SE*	*t*	*p*
(Intercept)	2.606	0.017	153.826	<0.01
Syllable number	0.022	0.009	2.415	**0.018**
TOWRE-sum	-0.055	0.015	-3.539	**0.001**
Word frequency	-0.03	0.01	-3.201	**0.002**
AoA	0.044	0.009	4.638	**<0.01**
Syllable number * TOWRE-sum	-0.008	0.006	-1.347	0.178
Random Effects	**Var.**	**SD**	**Corr.**	
Item intercept	0.004	0.063		
Subject intercept	0.102	0.101		
Residual	0.055	0.234		

Table B4. LMM Analyses Showing Gaze duration as a Function of TOWRE- Sight word efficiency score and Number of syllables

Fixed effects	*b*	*SE*	*t*	*p*
(Intercept)	2.608	0.018	143.168	<0.01
Syllable number	0.022	0.009	2.413	**0.018**
TOWRE-SWE	-0.027	0.017	-1.623	0.111
Word frequency	-0.03	0.01	-3.195	**0.002**
AoA	0.044	0.009	4.635	**<0.01**
Syllable number * TOWRE-SWE	-0.011	0.006	-1.976	**0.048**

Random Effects	Var.	SD	Corr.
Item intercept	0.004	0.063	
Subject intercept	0.102	0.111	
Residual	0.055	0.234	

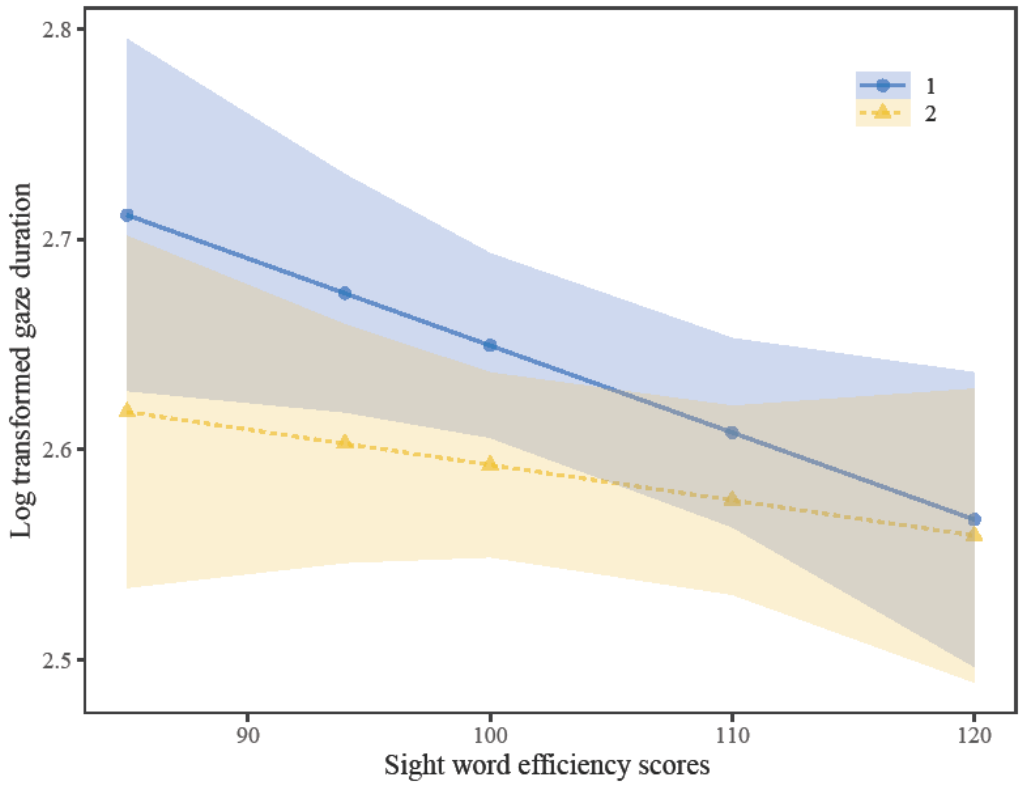

Figure B1. Plot showing interaction between sight word efficiency score and syllable number on log transformed gaze duration.

Table B5. LMM Analyses Showing Gaze duration as a Function of TOWRE- Phonemic decoding efficiency score and Number of syllables

Fixed effect	*b*	*SE*	*t*	*p*
(Intercept)	2.605	0.016	163.888	<0.01
Syllable number	0.022	0.009	2.416	**0.018**
TOWRE-PDE	-0.068	0.014	-4.797	**<0.01**
Word frequency	-0.03	0.009	-3.201	**0.002**
AoA	0.044	0.009	4.641	**<0.01**
Syllable number* TOWRE-PDE	-0.003	0.006	-0.539	0.59
Random Effects	**Var.**	**SD**	**Corr.**	
Item intercept	0.004	0.063		
Subject intercept	0.009	0.092		
Residual	0.055	0.234		

Table B6. LMM Analyses Showing Gaze duration as a Function of WIAT-II-T-spelling subtest score and Number of syllables

Fixed effects	*b*	*SE*	*t*	*p*
(Intercept)	2.607	0.017	157.843	<0.01
Syllable number	0.022	0.009	2.399	**0.019**
Spelling	-0.061	0.015	-4.097	**<0.01**
Word frequency	-0.030	0.01	-3.191	**0.002**
AoA	0.044	0.009	4.629	**<0.01**
Syllable number* Spelling	0	0.006	-0.048	0.962
Random Effects	**Var.**	**SD**	**Corr.**	
Item intercept	0.004	0.064		
Subject intercept	0.010	0.100		
Residual	0.055	0.234		

Table B7. LMM Analyses Showing Gaze duration as a Function of RAN-Numbers score and Number of syllables

Fixed effects	*b*	*SE*	*t*	*p*
(Intercept)	2.608	0.019	139.901	<0.01
Syllable number	0.022	0.009	2.416	**0.018**
RAN-numbers	0.002	0.017	0.143	0.887
Word frequency	-0.03	0.01	-3.202	**0.002**
AoA	0.044	0.009	4.631	**<0.01**
Syllable number* RAN-numbers	-0.003	0.006	-0.447	0.655
Random Effects	**Var.**	**SD**	**Corr.**	
Item intercept	0.004	0.064		
Subject intercept	0.013	0.115		
Residual	0.055	0.234		

Table B8. LMM Analyses Showing Gaze duration as a Function of RAN-Letters score and Number of syllables

Fixed effects	*b*	*SE*	*t*	*p*
(Intercept)	2.608	0.019	140.514	<0.01
Syllable number	0.022	0.009	2.418	**0.018**
RAN-letters	-0.011	0.017	-0.662	0.511
Word frequency	-0.03	0.01	-3.203	**0.002**
AoA	0.044	0.009	4.646	**<0.01**
Syllable number: RAN-letters	-0.005	0.006	-0.862	0.389
Random Effects	**Var.**	**SD**	**Corr.**	
Item intercept	0.004	0.064		
Subject intercept	0.132	0.114		
Residual	0.055	0.234		

Table B9. LMM Analyses Showing Gaze duration as a Function of WASI-Vocabulary score and Number of syllables

Fixed effects	*b*	*SE*	*t*	*p*
(Intercept)	2.607	0.018	145.134	<0.01
Syllable number	0.022	0.009	2.418	**0.018**
WASI-Vocabulary	-0.035	0.016	-2.115	**0.039**
Word frequency	-0.03	0.01	-3.206	**0.002**
AoA	0.044	0.009	4.633	**<0.01**
Syllable number* WASI-Vocabulary	0.001	0.006	0.088	0.93
Random Effects	**Var.**	**SD**	**Corr.**	
Item intercept	0.004	0.064		
Subject intercept	0.120	0.110		
Residual	0.055	0.234		

APPENDIX C

Chapter 4 Supplementary Material

Table C1. Descriptive statistics for fixation types excluding regressive fixations

Fix-type	N	EVS at Fixation Onset	EVS at Fixation Offset	Change in EVS	Fixation duration
Intra-line	24762	13.5 (5.3)	9.2 (4.8)	4.5 (2.7)	347 (198)
Line-final	1309	13.5 (4.5)	8.7 (4.2)	5.0 (3.2)	365 (230)
Accurate line-initial	687	13.8 (5.3)	8.06 (4.8)	6.1 (3.1)	442 (185)
Undersweep	1098	17.0 (5.2)	14.9 (4.8)	2.2 (1.4)	163 (59)

Table C2. LMM analyses showing log-transformed fixation durations as a function of the EVS and fixation type (including return-sweep regressions)

Fixed effects	*b*	*SE*	*t*	*P*
(Intercept)	2.4651	0.0095	260.1909	<0.01
EVS	0.0204	0.0031	6.6714	**<0.01**
Line-final	-0.0249	0.0069	-3.6236	**<0.01**
Accurate	0.1606	0.0106	15.0866	**<0.01**
Undersweep	-0.2971	0.0111	-26.8529	**<0.01**
Fixated word frequency	-0.0191	0.002	-9.6482	**<0.01**
Fixated word length	-0.0282	0.002	-13.9274	**<0.01**
EVS*Line-final	0.0726	0.0102	7.0919	**<0.01**
EVS*Accurate	-0.0274	0.0158	-1.7303	*0.0836*
EVS*Undersweep	0.0395	0.0128	3.0861	**0.002**
Fixated word Freq * Fixated word Len	-0.0114	0.0016	-7.1161	**<0.01**
Random effects	**Var.**	**SD**	**Corr.**	
Item intercept	0.0001	0.0105		
Participant intercept	0.0043	0.0659		
EVS slope	0.0003	0.0187	0.76	
Residual	0.0426	0.2064		

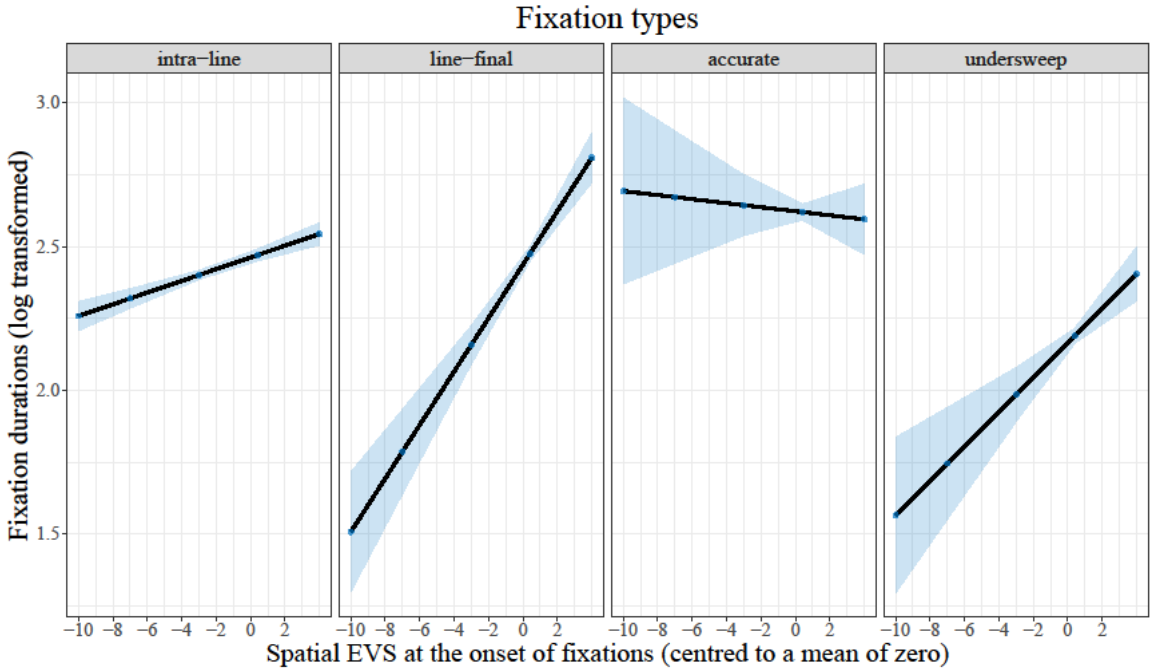

Figure C1. Line effect plots showing the interaction between the EVS and fixation type (including return-sweep regressions) for log-transformed fixation durations. Shading shows ± 1 SE.

Table C3. LMM analyses showing untransformed fixation durations as a function of the EVS and fixation type

Fixed effects	*b*	*SE*	*t*	*p*
(Intercept)	331.65	8.25	40.22	<0.01
EVS	16.68	3.03	5.5	**<0.01**
Line-final	-3.74	5.93	-0.63	0.53
Accurate	123.63	9.59	12.89	**<0.01**
Undersweep	-189.19	9.56	-19.79	**<0.01**
Fixated word frequency	-18.69	1.72	-10.9	**<0.01**
Fixated word length	-25.53	1.75	-14.56	**<0.01**
EVS*Line-final	59.75	8.84	6.76	**<0.01**
EVS*Accurate	-6.73	15.15	-0.44	0.66
EVS*Undersweep	26.93	11.07	2.43	**0.01**
Fixated word Freq * Fixated word Len	-13.05	1.39	-9.4	**<0.01**
Random effects	Var.	SD	Corr.	
Item intercept	74.04	8.60		
Participant intercept	3298.38	57.43		
EVS slope	372.43	19.30	0.78	
Residual	31764.17	178.23		

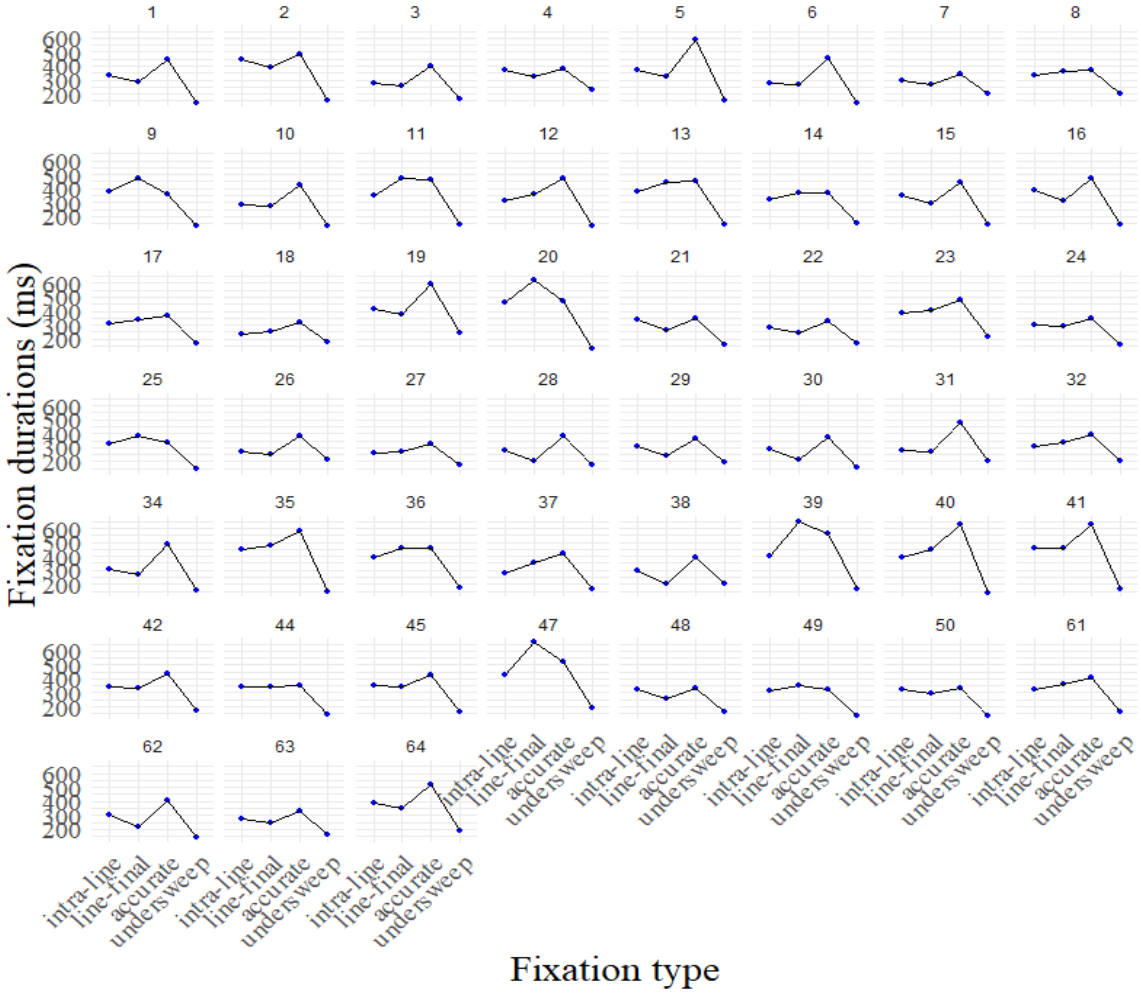

Figure C2. Mean fixation duration by fixation type for each participant

Table C4. LMM analyses showing log-transformed fixation durations as a function of the EVS, fixation type and grade.

Fixed effects	*b*	*SE*	*t*	*p*
(Intercept)	2.467	0.009	277.824	<0.01
EVS	0.02	0.003	6.594	**<0.01**
Line-final	-0.022	0.007	-3.185	**0.001**
Accurate	0.165	0.011	14.711	**<0.01**
Undersweep	-0.287	0.011	-25.463	**<0.01**
Grade 3-4	-0.021	0.017	-1.239	0.221
Grade 4-5	-0.027	0.015	-1.767	0.084
Fixated word frequency	-0.019	0.002	-9.76	**<0.01**
Fixated word length	-0.028	0.002	-14.022	**<0.01**
EVS*Line-final	0.08	0.01	7.734	**<0.01**
EVS*Accurate	0.007	0.018	0.355	0.723
EVS*Undersweep	0.023	0.013	1.756	*0.079*
Line-final*Grade 3-4	-0.018	0.017	-1.02	0.308
Accurate *Grade 3-4	-0.013	0.027	-0.473	0.636
Undersweep *Grade 3-4	0.022	0.019	1.161	0.246
Line-final*Grade 4-5	-0.052	0.015	-3.461	**0.001**
Accurate *Grade 4-5	-0.024	0.024	-1.009	0.313
Undersweep *Grade 4-5	0.099	0.017	5.678	**<0.01**
Fixated word Freq *				**<0.01**
Fixated word Len	-0.011	0.002	-7.122	
Random effects	**Var.**	**SD**	**Corr.**	
Item intercept	0.0001	0.0106		
Participant intercept	0.0037	0.0608		
EVS slope	0.0003	0.0189	0.74	
Residual	0.0425	0.2061		

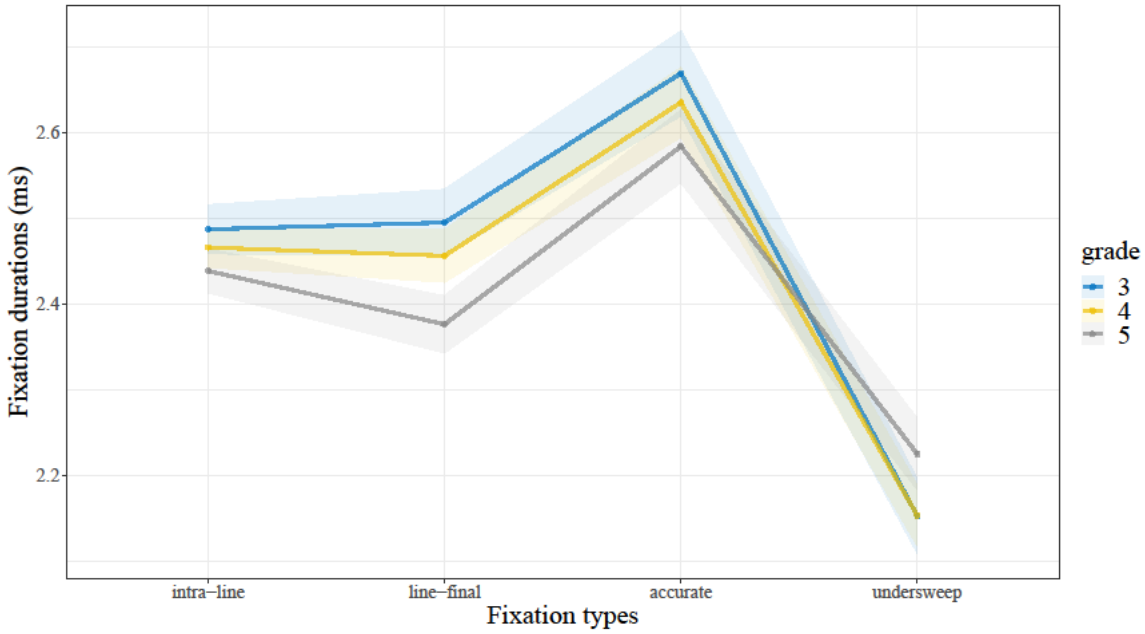

Figure C3. Line effects plot showing interaction between fixation type and grades for log-transformed fixation durations. Shading shows ± 1 SE.

Table C5. LMM analyses showing untransformed articulation rates measured with phonemes per second as a function of EVS and Word Position

Fixed effects	*Articulation rate (Phonemes per second)*			
	b	*SE*	*t*	*p*
(Intercept)	10.58	0.23	46.36	<0.01
EVS	1.26	0.11	11.95	**<0.01**
Line-final	0.04	0.12	0.34	0.74
Line-initial	0.14	0.11	1.25	0.21
Frequency	1.09	0.03	40.82	**0.01**
EVS* Line-final	0.11	0.13	0.89	0.37
EVS* Line-initial	-0.02	0.13	-0.14	0.89
Random effects	Var.	SD	Corr.	
Item intercept	0.20	0.45		
Participant intercept	2.50	1.58		
EVS slope	0.50	0.70	-0.29	
Residual	16.40	4.04		

APPENDIX D

Chapter 5 Supplementary Material

Table D1. Standardized offline ability scores for data in Chapter 5

Offline ability measures	Mean	SD	Min	Max
TOWRE-II	105.52	9.49	87	121
WIAT-II-T Spelling	104.35	12.36	78	130
RAN/RAS	105.48	9.62	83	123
WASI-II Vocabulary	57.08	10.17	37	77

Table D2. Reliabilities and descriptive statistics for eye movement measures obtained for children's silent reading (Parker et al., 2020)

Measure (N=52)	Mean	SD	Minimum	Maximum	Reliability
First fixation duration	273	58	193	489	0.97
Gaze duration	384	94	249	698	0.96
Total viewing time	536	205	288	1086	0.97
Skipping probability	0.01	0.01	0.00	0.06	0.67

APPENDIX E

Chapter 6 Supplementary Material

Table E1. LMM Analyses Showing Log-transformed Gaze Duration as a Function of Frequency and Length of Concurrently Articulated Words for Full Dataset

Fixed effects	*b*	*SE*	*t*	*p*
(Intercept)	2.527	.0112	225.152	<.01
ArtWordFreq	.004	.004	1.150	.250
ArtWordLen	.005	.004	1.368	.171
FixWordFreq	-.033	.004	-8.784	**<.01**
FixWordLen	-.003	.004	-0.676	.499
PrevWordFreq	-.023	.004	-5.608	**<.01**
PrevWordLen	-.014	.004	-3.378	**<.01**
FixLen*FixFreq	-.015	.003	-5.041	**<.01**
Random effects	Var.	SD		
Item intercept	<.001	.009		
Part. intercept	.006	.077		
Residual	.052	.227		

Statistically and marginally significant *p* values are formatted in bold and italics respectively

Table E2. LMM Analyses Showing Log-transformed Articulation Duration as a Function of Frequency and Length of Concurrently Fixated Words for Full Dataset

	b	*SE*	*t*	*p*
(Intercept)	2.489	.011	233.878	<.01
FixWordFreq	-.004	.002	-2.305	**.0212**
FixWordLen	-.003	.002	-1.579	.116
ArtWordFreq	-.109	.002	-66.347	**<.01**
ArtWordLen	.078	.002	46.905	**<.01**
Freq * Len	.019	.001	15.197	**<.01**
Random effects	Var.	SD	Corr.	
Item intercept	<.001	.019		
Length slope	<.001	.001	0.19	
Participant intercept	.006	.075		
Residual	.021	.144		

Note. Statistically and marginally significant *p* values are formatted in bold and italics respectively

APPENDIX F

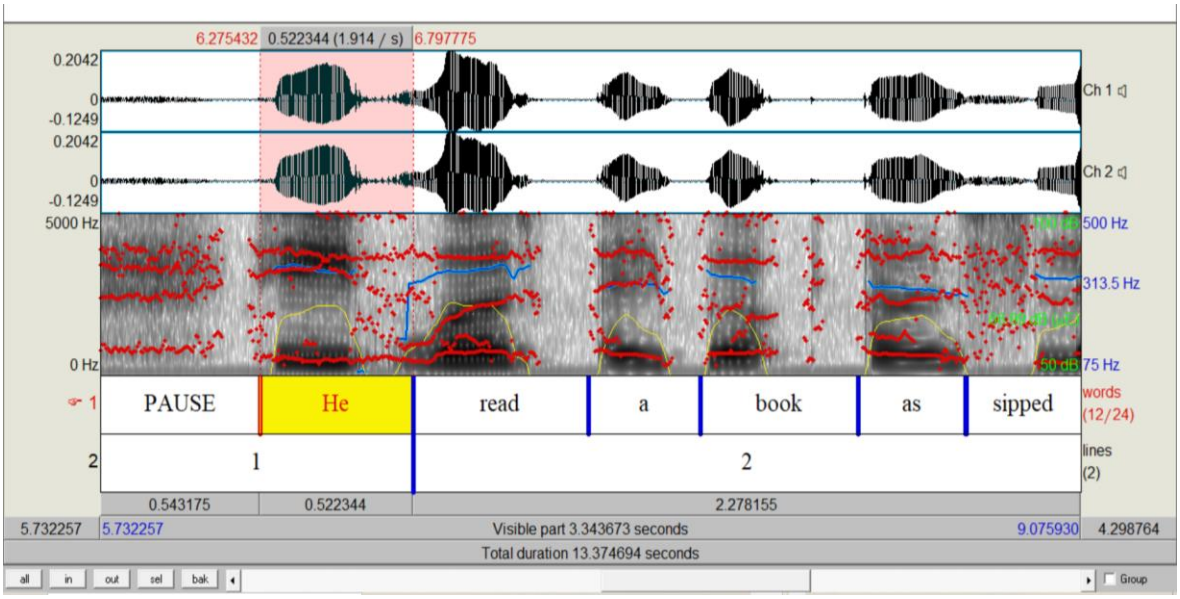

Figure F1. Sample PRAAT annotation.