

CHAPTER FOUR: The Eye-voice Span within and between Lines

4.1. Abstract

When reading aloud, the eyes are usually two or three words ahead of the voice. Research shows that skilled adult readers regulate this distance called the eye-voice span (EVS) by increasing fixation durations to avoid overloading working memory. In this study, we tested this pattern for the first time in children and examined whether this effect differs across line boundaries. The differential effect of the EVS on fixations was investigated by comparing fixations adjacent to the return-sweep (line-final and line-initial fixations) to intra-line fixations. In addition, we explored whether children increased their articulation rates when the EVS was large. By analysing eye movements and voice data from 51 children who read short passages spanning two lines, we reported a similar effect of the EVS on fixation durations found in skilled readers. A larger EVS at the start of a fixation was associated with increased fixation durations. Importantly, this effect was more pronounced for line-final and a sub-type of line initial fixations, namely: undersweep fixations compared to intra-line fixations. These results suggest that moving between lines may be more costly during oral reading and contribute significantly to longer reading times in children who primarily read aloud. Articulation rates were also higher when the EVS was large compared to when it was small, suggesting that the eye and the voice work dynamically to ensure the optimal amount of information is buffered in working memory.

4.2. Introduction

Oral reading is a complex task that involves the concurrent recruitment of visual, oculomotor, lexical, semantic, memory, and articulatory processes (Godde et al., 2021; Inhoff & Radach, 2014; Kim et al., 2019). Unlike skilled readers, children who are yet to acquire efficient word recognition skills often struggle to produce fluent speech and comprehend text simultaneously (Blythe & Joseph, 2011; Reichle et al., 2013; Vorstius et al., 2014). Reading passages aloud across multiple lines rather than single lines may amplify these difficulties (Adedeji et al., 2021; Levasseur et al., 2006; van Silfhout et al., 2014). During multiline oral reading, readers need to move their eyes from the end of one line to the beginning of the next while coordinating the distance between the eye and

voice. This distance, called the eye-voice span (EVS), occurs because speech rates are typically slower than eye movements (Adedeji et al., 2021; Brysbaert, 2019; Laubrock & Kliegl, 2015).

The evidence from single-line reading studies reveals that, for adults, when the EVS goes beyond the capacity of working memory (Geyer, 1967), eye movements are constrained, and fixation durations increase (Inhoff et al., 2011; Laubrock & Kliegl, 2015). However, what remains unexplored is whether this modulation is the same when moving from one line to another. Additionally, the EVS reflects the dynamic relationship between the eyes and voice, which constantly changes depending on text demands. Therefore, readers can either slow down their eyes to allow the voice catch up or speed up their articulation to catch up with the eyes (Fairbanks, 1937). With most researchers focusing on the former, less is known about the latter possibility. For instance, would readers speedup or slowdown their articulation rates when the EVS is large or small or do articulation rates remain constant regardless of the size of the EVS? It is unknown whether this dynamic relationship is obtainable for developing readers. Therefore, the current study examined how the width of the EVS impacts children's fixation durations around line boundaries compared to their fixation durations within lines. We investigated whether articulation rates are affected by the EVS, which has not been empirically tested in children or adults. We begin with a description of eye movements occurring within and between lines.

4.2.1. Eye Movements Within and Between Lines

During reading, eye movements move the fovea (the part of the visual field where acuity is highest) to various text locations to optimise visual and linguistic processing. As such oculomotor behaviour reflects the cognitive processes involved in reading (Just & Carpenter, 1980; Liversedge & Findlay, 2000; Radach et al., 2007; Reichle et al., 1998). Two critical measures of eye movements are saccades and fixations. *Saccades* are the eye movements that take our gaze from one point in the text to the next. *Fixations* are the short pauses that occur between saccades and allow the processing of information.

Intra-line fixations and saccades can be defined as occurring within the same line of text (Parker, Slattery, et al., 2019; Vasilev et al., 2021). Intra-line fixations are about 250ms for adults and 280ms for children while intra-line saccades are 8 character spaces for adults and 7 character spaces for children (Blythe et al., 2006; Rayner, 1998). Due to different linguistic and oculomotor factors, skilled and developing readers show considerable variability in these measures. Linguistic variables such as word frequency

(Kliegl et al., 2004; Schilling et al., 1998; Staub et al., 2010; White, 2008), predictability (Rayner, Reichle, et al., 2006; Staub, 2015), syntactic ambiguity (see Clifton Jr et al., 2007 for a review), and parafoveal processing (Henderson & Ferreira, 1990; Kliegl et al., 2006; Schotter et al., 2012) influence intra-line eye movements. For instance, readers fixate more frequent and predictable words for less time compared to less frequent and predictable words. However, such effects are more pronounced in children than in adults (Joseph et al., 2009; Tiffin-Richards & Schroeder, 2015b). Similarly, intra-line eye-movements are influenced by visuomotor factors such as word-initial fixation location (Vitu et al., 2001; Vitu et al., 1990) and word length (Hautala & Loberg, 2015; Kliegl et al., 2004). For example, readers' initial saccade landing position within a word depends on word length (Joseph et al., 2009; Rayner, 1979). At the same time, fixation duration is a function of this position where fixations are longer when landing positions are closer to the word's centre (Inverted Optimal Viewing Position; Vitu et al., 2001).

Current models of eye movement control agree that both higher-order linguistic and low-level visuomotor factors are necessary to explain the variation in intra-line eye movement patterns (e.g., E-Z reader; Reichle et al., 2013; Reichle et al., 2003; Reichle et al., 1999). However, they may disagree on the relative importance of each factor. For instance, the E-Z reader (Reichle et al., 2003) and SWIFT models (Engbert et al., 2005) emphasise cognitive influences, while the Competitive Interactive Model (Yang & McConkie, 2001) emphasises oculomotor processes. These models have mostly been developed on data from intra-line eye movements. However, eye movements between lines are far less studied. This is interesting as saccades between lines may not be subject to the same level of linguistic and oculomotor control as intra-line saccades (Parker et al., 2020; Slattery & Vasilev, 2019).

Return-sweeps are one example of such saccades between lines. They are the long saccades that take readers' gaze from the end of one line to the beginning of the following line. Two distinct fixation types occur next to return-sweep saccades: line-final and line-initial fixations. Line-final fixations occur immediately prior to launching a return-sweep saccade. These are around 25ms shorter than intra-line fixations (Adedeji et al., 2021; Parker, Nikolova, et al., 2019; Parker & Slattery, 2021). Linguistic-control theories (Rayner, 1977) explain this speed-up at the end of the line as a consequence of the absence of parafoveal information. That is, there is far less parafoveal information to the right of the line-final fixations to process compared to intra-line fixations. Oculomotor accounts (Kuperman et al., 2010; Mitchell et al., 2008) propose that this difference occurs because line-final fixations serve mainly to plan and execute return-sweeps and are thus less

influenced by text processing. Previous and recent research endeavours provide support for this account. Hofmeister (1997) found that reducing the saliency of text through degradation, increased fixations durations of all fixations except line-final fixations. Additionally, Parker, Slattery, et al. (2019) reported that children aged 6 to 9 years and adults showed similar line-final speed-up effects supporting the oculomotor account. However, reading ability influences line-final fixations the same way as other reading fixations, which weakens a sole oculomotor planning account and permits the consideration of an integrative account (Parker & Slattery, 2021).

Previous research has established two classes of line-initial fixations that could follow the return-sweep saccade. Accurate line-initial fixations land near the left margin and do not require a leftward correction, while undersweep fixations land away from the left margin requiring a leftward corrective saccade (Parker & Slattery, 2019; Parker, Slattery, et al., 2019). Regardless of which line-initial fixation occurs, the return-sweep is thought to be targeted towards an area close to the left margin rather than word centres like intra-line saccades (Slattery & Vasilev, 2019). Accurate line-initial fixations are usually longer than intra-line fixations in adults (Hofmeister, 1998; Hofmeister et al., 1999; Parker, Slattery, et al., 2019; Rayner, 1977), presumably because the target of this fixation has not been parafoveally previewed, as is the case for intra-line targets. In view of this, spelling ability which indexes early orthographic encoding influences the duration of accurate line-initial fixations but not intra-line fixations which have access to parafoveal information (Parker & Slattery, 2021). A complementary oculomotor assumption is that these fixations could be responsible for saccade planning processes over the whole line (Kuperman et al., 2010; Parker, Slattery, et al., 2019; Pynte & Kennedy, 2006). However, during silent reading, children show no significant difference between accurate line-initial and intra-line fixations compared to adults due to their reliance on foveal processing more generally and piecemeal saccade planning over the line (Parker, Slattery, et al., 2019). That is, the rate of foveal processing appears stable for accurate line-initial and intra-line fixations for developing readers.

Undersweep fixations occur 40-60% of the time and are the shortest among all fixation types (~75ms shorter than intra-line fixations; Adedeji et al., 2021; Parker, Nikolova, et al., 2019; Parker & Slattery, 2021). These fixations are short because they are terminated due to retinal feedback from landing in a suboptimal location at the start of the line (Abrams & Zuber, 1972; Hofmeister et al., 1999; Parker, Nikolova, et al., 2019; Parker, Slattery, et al., 2019). In fact, the likelihood of these fixations increases exponentially with greater landing distance from the left margin (Parker, Slattery, et al.,

2019). Undersweep fixations have traditionally been thought to be independent from linguistic processing and reflect the oculomotor programming of a corrective saccade (Abrams & Zuber, 1972; Hofmeister et al., 1999). Nevertheless, recent research has suggested that at least some pre-lexical information may be obtained at the point or to the left of this fixation (Parker et al., 2020; Slattery & Parker, 2019).

The leftward saccade that follows an undersweep fixation, aims to adjust the fovea to a location that maximises visual processing near the beginning of the line (Andriessen & de Voogd, 1973; Hofmeister, 1998; Hofmeister et al., 1999; Slattery & Vasilev, 2019). Hence, they are called corrective saccades. Unlike undersweep fixation durations, the likelihood of a corrective saccade (likelihood of an undersweep fixation) is dependent on global cognitive processing demands. For example, more corrective saccades are associated with less skilled reading (Molina et al., 2020; Parker, Slattery, et al., 2019; Trauzettel-Klosinski et al., 2010), less skilled spelling (Parker & Slattery, 2021), complex texts, and task instruction (Heller, 1982). Corrective saccades are also dependent on physical text characteristics such as font size (Hofmeister, 1998; Vasilev et al., 2021), length of the previous line (Hofmeister et al., 1999; Vasilev et al., 2021), and the saliency of the target (Slattery & Vasilev, 2019). Therefore, text characteristics that increase the visibility of return-sweep targets and reduced demands on cognitive processing generally lead to more accurate return-sweep targeting. In summary, both linguistic and oculomotor factors influence eye-movements at line boundaries.

4.2.2. Eye movements during multiline oral reading

Eye-movements have mostly been studied during silent reading. However, there are differences when a text is read aloud. In Chapter two (Adedeji et al., 2021), intra-line fixations are longer, regressions are more frequent, and saccade lengths are shorter during oral reading compared to silent reading in children and adults consistent with previous studies (Anderson & Swanson, 1937; Kim et al., 2019; Krieber et al., 2017; Vorstius et al., 2014). Linguistic effects commonly present in silent reading, such as word frequency, are reduced in oral reading (Vorstius et al., 2014). Additionally, during oral reading, there is a reduction in the perceptual span- the spatial region from which useful information is obtained during a fixation (Ashby et al., 2012; Inhoff & Radach, 2014; Pan et al., 2017).

These differences exist because the rate of spoken language is 150 words per minute (WPM), which is slower than typical silent reading rates (250 WPM; Brysbaert, 2019). Therefore, speech processes limit how far eye movements can go during oral reading (Kim et al., 2019; Levin & Addis, 1979). For skilled readers, whose efficient lexical skills

are reflected in rapid eye movements, there is a tendency for the voice to trail behind the eyes (Vernon, 1931). This lag results in the widening of the EVS. Buswell (1920) first associated the width of the EVS with the attentional capacity to hold multiple words in the mind at a given time. In the light of working memory models (Baddeley, 2010; Baddeley & Hitch, 2019), phonological information of perceived words is rehearsed in the phonological loop component of working memory for later articulation. Because working memory capacity is limited, a large EVS implies that previously perceived words that are yet to be articulated will be prone to forgetting and errors. This would in turn disrupt the normal reading flow through regressive saccades (Geyer, 1967) as more regressions have been associated with lower oral reading rates (Søvik et al., 2000). In such instances, Laubrock and Kliegl (2015) and Inhoff et al. (2011) showed that single fixation durations, refixations and regressions are increased to hold back the eyes. A reduction in the rate of new visual and linguistic processing keeps the EVS within limits. One can conceive that this oculomotor mechanism may operate by delaying the rightward shift of attention once lexical access is completed for the current word, as in the E-Z reader model of eye movements (Inhoff et al., 2011; Reichle et al., 2009). Although delays in eye movements due to the width of the EVS have not been documented for children, many researchers report that children as young as 7 years have an EVS of 8-character spaces (see Table 1.1). There is also a clear developmental pattern in the EVS (Cohn & Levin, 1967; Holgerson, 1977; Levin & Turner, 1966; Resnick, 1970) which has been reported to be largely dependent on reading skills as reported in [Chapter 3](#).

The studies by Laubrock and Kliegl (2015) and Inhoff et al. (2011) on how the EVS limits eye movements were conducted with single-line stimuli. However, the experiment in Chapter 2 which examined return-sweep saccades in multiline oral reading compared to silent reading suggests this constraint may differ at line boundaries (Adedeji et al., 2021). Adedeji et al. (2021) examined return-sweep planning and execution differences between oral and silent reading. They replicated the effect of increased intra-line fixation durations during oral reading compared to silent reading. Additionally, a marginally and significantly greater effect of oral reading on line-final fixations and accurate line-initial fixations, respectively, compared to intra-line fixations was reported. This suggested that readers attempted to reduce the EVS around line boundaries by increasing fixation durations. A positive relationship between the EVS and fixation durations (Inhoff et al., 2011; Laubrock & Kliegl, 2015) within a reader, suggests that smaller EVSs may precede shorter fixation durations. Considering this relationship, the EVS may be shorter at the end of the line compared to the beginning of lines given line-final speed-up effects.

Indeed, early research reports that the EVS is smallest at the end of lines compared to the beginning (differences of 1.8 letter spaces: Buswell, 1920; 6 letter spaces: Fairbanks, 1937; and 4.6 words: Quantz, 1897). However, different methods have been used to derive these estimates, warranting a more detailed analysis. Buswell (1920) used each word's articulation as a reference measurement point, i.e., the distance between the first character of the to-be-articulated word and the fixation location at the same time³. With the measure, the EVS at the end of the line is EVS for the line-final word rather than the line-final fixation. Therefore, we cannot conclude that Buswell's difference simulates the EVS-fixation duration relationship.

An alternative is calculating the EVS at the beginning of each fixation rather than at the time of each word's utterance (Fairbanks, 1937). This method allows a more fine-grained assessment of moment-by-moment modulation of the EVS during reading because words can receive more than one fixation. Importantly, this approach allows us to examine how the EVS impacts specific types of fixations within and between lines, as discussed in the previous section. Fairbanks (1937) reported a 6-character-space difference in EVS between the end of the line (line-final EVS) and beginning of the line (line-initial EVS). Higher than average EVS at line-initial fixation was attributed to return-sweep inaccuracies, i.e., undersweep fixations. However, there was no difference between the line-final EVS and the average EVS of forward fixations. This study indicates that the EVS for forward fixations may be similar to line-final fixations, at least for skilled readers. However, no clarity was given regarding within line fixations (intra-line) or first fixations on a new line followed by a rightward saccade (accurate line-initial).

What remains unknown is whether developing readers exhibit the same pattern of EVS changes within and between lines (Fairbanks, 1937), as well as modulation in the EVS (Laubrock & Kliegl, 2015), like adults. Oral reading appears to be more costly at line boundaries as launch and landing positions are closer to the margin compared to silent reading. Additionally, the probability of making corrective saccades is greater in oral reading than in silent reading. These patterns have also been replicated in children's silent reading, where return-sweeps launched and landed closer to the margins, and corrective saccades were greater compared to adults (Parker, Slattery, et al., 2019). Research shows a tendency for children's eye movements during silent reading and oral fluency during oral reading to be disrupted by line boundaries compared to skilled readers. In a longitudinal silent reading study, Tiffin-Richards and Schroeder (2018) found that grade

³ This method allows the assessment of EVS impact on speech output.

two children (7 years) did not exhibit speed-up effects for line-final words compared to the same children in grades three and four. Additionally, they often initiated regressions at line-final words rather than at clause or sentence-final words which was typical of skilled readers. During oral reading, Levasseur et al. (2006) reported that 8 and 9-year-olds were less fluent and stumbled more at line boundaries in a condition where end of lines did not coincide with clause boundaries compared to a condition where line-ends and clause boundaries were nonoverlapping. On the contrary, older students in eighth grade (~13 year olds) showed reduced fixation times on line-initial regions in continuous texts (with overlapping line and sentence boundaries) compared to discontinuous texts (van Silfhout et al., 2014). Therefore, it appears oral reading of multiline text may be difficult for developing readers compared to skilled readers. Overall, these studies indicate that line boundaries offer an interesting region to better understand developmental oral reading.

4.2.3. The Present Study

Line boundaries appear to be more costly for developing readers and this cost may be greater during oral reading where readers need to co-ordinate the voice output and eye movements compared to silent reading. Therefore, this study investigated the coordination of the eyes and voice during oral reading of two-line passages in order to compare how the EVS affects eye movements within the line for children compared to eye movements at line boundaries. The first objective was to present a description of the EVS within and between lines using a fixation-based measure as previous research involved undergraduate readers (Fairbanks, 1937). Specifically, we investigated how the EVS changes from the start to the end of each fixation type (i.e., intra-line, line-final, accurate line-initial and undersweep). Second, we investigated how influential the EVS is in determining the fixation durations for each fixation type. In Chapter 2, readers pausing more at line boundaries was attributed to EVS modulation (Adedeji et al., 2021). Additionally, line boundaries are more costly for developing readers compared to skilled readers (Levasseur et al., 2006; Parker, Slattery, et al., 2019; Tiffin-Richards & Schroeder, 2018). In this study, we propose that eye-voice coordination and return-sweep planning may induce greater cognitive processing demands. This proposition predicts that the EVS may impact fixation durations around the return-sweep, i.e., line-final and accurate line-initial fixations to a greater degree compared to intra-line fixations. Modulating fixation durations at the end of the line may be necessary to allow a reasonable reduction in the EVS before making a potentially costly return-sweep to the

following line. If readers execute a return-sweep prior to adequately encoding the text from that line, they may need to regress to the end of the line to complete their encoding. Such long-distance regressions would likely be more disruptive to the reading process than typical intra-line regressions and require an additional return-sweep saccade. Prior research shows that regressions to previous lines are less common than intra-line regressions (Ehrlich & Rayner, 1983). The EVS may also strongly modulate readers' accurate line-initial fixations, as these fixations may provide some time to synchronise the eye and voice before progressing through the new line. These are cogent areas of inquiry because Laubrock and Kliegl (2015) reported a more substantial influence of the EVS on single fixation durations than word length and frequency effects. Due to the involvement of undersweeps in low-level oculomotor processes, we did not expect these fixations to be affected by the EVS.

Third, we explored whether the EVS at the end of the line-final fixation influences return-sweep targeting, i.e., landing positions and corrective saccade probability. Inhoff et al. (2011) reported that large EVSs beyond 600ms predicted shorter outgoing saccade lengths within lines. Although the targets of return-sweep and intra-line saccades may differ (McConkie et al., 1988; Slattery & Vasilev, 2019), the effect of reading modality (Adedeji et al., 2021) and font size (Vasilev et al., 2021) on the targeting (landing positions) are similar for both kinds of saccades. Therefore, allocating attention to articulatory processes when the EVS is wide at the end of the line may influence how far the return-sweep saccade lands on the new line. We expected that if the EVS was large prior to launching the return-sweep saccade, landing positions might shift leftward to ensure a smaller span between the eye and voice. Corrective saccades are more common in children compared to adults (Parker, Slattery, et al., 2019) and children with ADHD or dyslexia compared with typical children (Molina et al., 2020; Trauzettel-Klosinski et al., 2010). Additionally, oral reading induces more corrective saccades compared to silent reading (Adedeji et al., 2021). Given that these greater processing demands, or difficulties lead to more corrective saccades even for leftward landing positions (see Parker, Slattery et al., 2020 and Parker & Slattery, 2021), we proposed that larger EVS before the return-sweep saccade is made, may interfere with the accuracy of the return-sweep saccade. Corrective saccades could also aid in modulating the EVS, where a larger span increases the probability that a leftward saccade follows the line-initial fixation to keep the eye closer to the voice. While these two predictions seem counterintuitive, previous research has shown that an increase in corrective saccade probability and leftward landing positions are both associated with oral reading (Adedeji et al., 2021), children (Parker,

Slattery, et al.), 2019, poor spellers (Parker & Slattery, 2021) compared to silent reading, adults and good spellers respectively. This indicates that both eye movement patterns are distinct and may depend on different mechanisms, i.e., leftward landing position may be due to dependence on foveal processing and more corrective saccades may be due to farther saccadic targets.

Finally, we explored whether the EVS is modulated by articulation rate and if this modulation is different at line boundaries. According to Fairbanks (1937), "*The lead may be increased by forward movement of the eyes or by lagging of the voice; it is decreased by the reverse type of interaction*" (p. 85). Additionally, Laubrock and Kliegl (2015) assert "*Given that the voice proceeds fairly linearly through the text, most of the adjustment is actually performed by the oculomotor system*" (p.17). The present study allows us to test these propositions empirically for the first time and in a developmental sample.

4.3. Method

This section is partly taken from Chapter 3 (Adedeji et al., under revision) because the data analysed is a subset of the data collected for a larger project examining children's reading development.

4.3.1. Participants

Sixty-four children from two primary schools in Bournemouth participated in this research after school, parental and child consent was obtained. All participants were English monolinguals, except seven who spoke at least one other language. Results did not differ when including or excluding these participants, so their data were retained. No child had a prior diagnosis of reading disorders, and all reported normal or corrected-to-normal vision. Some participants' data were excluded due to technical errors (10), chance-level comprehension scores (1), excessive head movements (1), and no offline measure due to school absence (1). Therefore, the data from 51 participants between ages 7 to 10 years across grades three, four and five (27 female, *Mean*= 8.89, *SD*=0.93) were used in the current study. Participants completed the Test of Word Reading Efficiency 2- Form A (TOWRE; Torgesen et al., 1999) and Wechsler Individual Achievement Test II for Teachers (WIAT-II-T; Weschler, 2006), which confirmed age-appropriate reading levels (*Mean*= 105.51, *SD*=9.58) and normal intelligence (*Mean*= 109.16, *SD*= 15.84) respectively. All participants were naïve as to the purpose of the experiment. Bournemouth University's Research Ethics Committee approved the study (ID 28325).

4.3.2. Materials and Design

The experimental stimuli comprised 2 sets of 42 experimental passages each (see [Appendix A](#)); however, each participant only read 1 set. Each passage had between 70 and 101 characters ($M= 87.18$ characters, $SD= 8.03$) and two sentences spanning two double-spaced, left-justified lines. The first line contained an average of 48 characters (7 to 12 words; $M= 9.83$ words). The second line contained an average of 38 characters (4 to 12 words; $M= 7.73$ words). Six-letter target words of either one or two syllables were embedded in each passage, but this was not considered in the current analysis. All 84 passages were assessed for readability using Flesch-Kincaid reading ease metrics ($M= 2.36$, $SD= 0.92$). As each participant only read 42 passages, the assignment of participants to the different sets was counterbalanced.

4.3.3. Apparatus

The eye movement data were recorded with an SR Research EyeLink 1000 Plus desktop-mounted eye-tracker with a sampling frequency of 1000Hz. Reading was binocular, but eye movements from only the right eye were recorded (except for five participants who had the left eye recorded due to problems tracking their right eye). Stimuli were presented on a BenQ XL2410 T LCD monitor with a 1920 x 1080 screen resolution and 60 Hz refresh rate. Participants' voices were recorded using a Fifine USB Microphone –K056 Model device with a lag range of 3 to 24 ms. A forehead rest was used to minimise head movements. However, chin rest was not used to allow unhindered articulation while reading. The passage was presented in a black 22-point monospaced Consolas font on a white background. The text was presented vertically centred on the screen with a 550-pixel offset horizontally. The eye-to-screen distance was 70cm, and each letter subtended $\sim 0.34^\circ$ horizontally. Experimental programming was done in MATLAB R2018a (MathWorks, 2014) using the Psychtoolbox v.3.0.11 (Brainard, 1997; Pelli, 1997) and Eyelink (Cornelissen, Peters, & Palmer, 2002) libraries. The experiment was run on a Windows 7 operating system.

4.3.4. Procedure

Each participant gave written assent and was given verbal instructions before the experiment began. Participants were tested in quiet rooms within the school, where they completed two sessions. In one session, they completed an eye-tracking experiment, and in the other session, they completed a paper-and-pencil offline assessment of reading and

cognitive ability. The order of the sessions differed among participants, with some completing the eye-tracking experiment first and others the offline assessment first.

At the start of the eye-tracking experiment, participants were instructed to read the passages aloud and to say “done” once they were finished so that the experimenter could terminate the trial. After this, participants completed a 9-point calibration and validation procedure. Validation accuracy was always < 0.40 , and recalibration was done whenever the drift check fell below this level. Furthermore, recalibration was also done after a 2-minute break scheduled at the middle of the experiment. Participants’ fixation on a 50-pixel black gaze box centred on the first letter of the passage triggered its presentation. Three practice trials were completed to familiarise participants with the instructions. During the experiment, participants answered TRUE/FALSE comprehension questions that appeared after 14 passages (33%) by pressing one of two buttons on a keyboard. Both sessions lasted for approximately 1 hour, with opportunities for a break between sessions.

4.3.4. Data analysis

Eye-doctor v.0.6.5 (Stracuzzi & Kinsey, 2009) was used to manually pre-process eye movement data and align fixations vertically with preceding and successive fixations on the same line. Additionally, the EMreading R package (Vasilev, 2018) software generated fixation and word-level data for the analysis. PRAAT software (Boersma & Weenink, 2019) was used to manually pre-processed the audio data. The waveforms, spectrogram and formants were used to determine the onset of articulation for each word in the text. Whenever co-articulation occurred, effort was made to allocate the boundary to a midpoint between the two words. An R script was developed to merge eye fixation data with the audio textgrids and compute the Spatial EVS in character spaces and in words. Linear mixed models were used to analyse the data (lme4 package v1.1-21: Bates, Mächler, et al., 2015) in R software v 4.0.3 (R Core Team, 2020). Table 4.1 summarises the measures analysed in the current study.

In this chapter, data from all participants aged 7 to 10 were combined for the main analyses to enable some comparison between the data from Parker et al. (2019) where data from children in aged 6 to 9 were analysed for return-sweep planning and execution behaviour in silent reading. Importantly, although there is some variability in the eye movements of children within the current sample, their eye movements are still within the developing phase (Blythe & Joseph, 2011)

For all models, participants and items were treated as crossed random effects. Initially, we adopted a full random structure (Barr et al., 2013), with random intercepts

for participants and items and random slopes for the fixed effects. If this model did not converge, we used a parsimonious mixed model approach to remove random slopes and interactions with the least variance from the random effects structure (Bates, Kliegl, et al., 2015). The results were statistically significant if the $|t|$ values were ≥ 1.96 . Fixation type was treated as a fixed effect, and treatment contrast compared each fixation type to intra-line fixations. The EVS measures were included as centred predictors. Length and frequency of fixated words were included as statistical controls in the fixation and articulation rate models and were also centred (Kliegl et al., 2006). Due to skewed distributions, fixation durations and articulation rates were also log-transformed due to skewed distributions (untransformed analyses agreed with log-transformed analyses, see [Appendix C](#)). The distance from the left margin from which the return-sweep is launched was included in the models for landing positions and corrective saccade probability as launch site has been shown to impact return-sweep landing sites and corrective saccade probability in prior research (Vasilev et al., 2021). Cohen's d effect sizes are reported. Statistically and marginally significant p values are formatted in bold and italics respectively.

Table 4.1. Measures and their Operational Definitions

Measure	Sub-measure	Operational definition
Eye-voice span	Fixation-based measure	The distance in character spaces between the fixation location and the approximate phoneme the voice is uttering either at the fixation's start (ONSET) or end (OFFSET) ⁴ .
Return-sweep measures	Landing position	The number of character spaces from the start of the new line, the return-sweep saccade ended.
	Corrective saccade probability	The probability that a return-sweep saccade is immediately followed by at least one additional leftward saccade.
Fixation types	Intra-line	Fixations occurring within the line that are not adjacent to the return-sweep saccade
	Line-final	Fixations immediately prior to the return-sweep saccade
	Accurate line-initial	Fixations immediately after the return-sweep saccade, given that a rightward saccade follows the fixation
	Undersweep	Fixations immediately after the return-sweep saccade, given that a leftward saccade follows the fixation

4.4. Results

All participants had comprehension accuracy of at least 70%, indicating they read for meaning (mean: 85.3% *SD*: 35.4% range: 72.5-95%). Some fixations were discarded due to blinks occurring on them or on line-final and line-initial fixations (10.50%). Fixations less than 80ms that occurred within one character of a temporally adjacent fixation were combined with that fixation. All other fixations that were less than 80ms and greater than 1200ms were excluded from the analysis (2.33%). Additionally, fixations, where the corresponding speech data had errors and audio data had errors were excluded from the merged eye movement and audio data (3.40%). Fixations occurring after the articulation of the final word in the trial were also excluded (4.98%). This left a total of 78.80 % (49,206 observations) of the fixation data for analysis.

⁴ In line with Laubrock and Kliegl (2015) who distinguished between onset and offset EVS, including the offset measure allows us to ascertain the amount of EVS modulation that occurs during a fixation.

4.4.1. Characteristics of the EVS before and after the Return-sweep Saccade

Descriptive statistics for the EVS and fixation durations based on the different fixation types are reported in Table 4.2 and illustrated in Figure 4.1. Except for two accurate line-initial fixations, at the start of all line-initial fixations on line two, the voice was always on line one and was approximately three words on average behind the eyes for all fixation types except undersweep fixations (approximately four words behind the eyes).

The change in EVS from onset to offset was greater for accurate line-initial, $b=1.77$, $SE=0.12$, $t=14.50$, $p<.001$ and line-final fixations, $b=0.49$, $SE=0.08$, $t=6.18$, $p<.001$, but smaller for undersweep fixations, $b=-1.96$, $SE=0.09$, $t=-21.19$, $p<.001$ compared to intra-line fixations. These results indicate that the longer fixations allow for greater EVS reduction compared to shorter fixations. Clearly, the amount of EVS change is dependent on the duration of fixations.

Table 4.2. Mean (Standard deviation) EVS at Onset and Offset, and Fixation Duration of each Fixation Population

Fixation type	N	EVS at Fixation Onset	EVS at Fixation Offset	Change in EVS	Fixation duration
Intra-line	45434	10.6 (9.3) *	7.1(8.6)	4.2 (2.6)	334 (192)
Line-final	1883	12.7(5.6)	8.1(4.8)	4.3 (3.1)	340 (221)
Accurate line-initial	789	13.8 (5.3)	7.9 (4.8)	6.1 (3.1)	421 (194)
Undersweep	1100	17.0 (5.1)	14.9 (4.8)	2.2 (1.4)	163 (60)

Note: N: Number of observations. *The EVS at the start of intra-line fixations were considerably shorter than all other fixations due to higher proportion of regressive saccades occurring within the line (see Appendix C for data excluding regressive fixations).

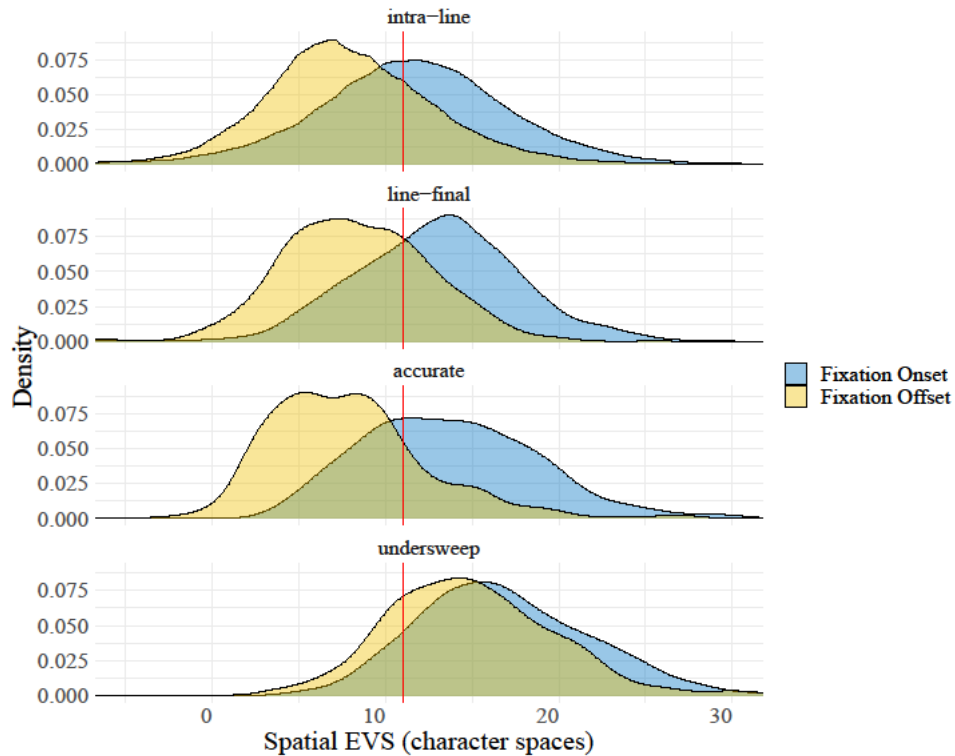


Figure 4.1. Distribution of spatial EVS at fixation onset and offset. Negative values indicate instances where the voice is ahead of the eyes. The red lines indicate the mean spatial EVS at fixation onset.

4.4.2. Eye Movements after the Return-sweep Saccade

After the return-sweep saccade landed on the new line, a proportion of fixations were followed by regressions to the previous line rather than to the left, as is the case for undersweep fixations or to the right as is the case for accurate line-initial fixations. We refer to these cases as “Return-sweep regressions”. These fixations were relatively rare (4.55 % of all line-initial fixations) and 70% of participants made a return-sweep regression at least once during the experiment. Still, the low number of observations prevents us from performing meaningful statistical comparisons with other line-initial fixations. Therefore, we excluded them in the subsequent inferential analysis in sections [4.4.3](#) and [4.4.5](#). However, Table 4.3 presents the means of eye movement and EVS measures for these fixations and other line-initial fixations. Numerically these fixations were longer in duration than undersweeps but shorter than accurate line-initial fixations. One clear pattern was that the number of words left to be uttered on line one when the return-sweep was made and the EVS at the end of the line-final fixation was numerically greater for return-sweep regressions compared to accurate line-initial or undersweep

fixations. For some perspective, we examined previous data sets to compare how frequently return-sweep regressions occur for children’s silent reading (Parker et al., 2020) and skilled adult reading in both reading modalities (Adedeji et al., 2021). Our re-analysis of the children’s data in Parker et al. (2020) showed that return-sweep regressions accounted for 7.56% of all line-initial fixations. However, re-analysis of data in Chapter 2 showed that return-sweep regressions were more frequent in oral reading (2.4%) than in silent reading (1.8%) in the adult reading data.

Table 4.3. Means (Standard Deviations) of Line-initial Fixation Characteristics

Line initial fixation	N	Fixation duration	Onset EVS	Offset EVS	EVS change	Launch position	Landing position	No. of words left to be uttered when the RS is made	Line-final fixation offset EVS	Line-final fixation duration
Accurate	695	428 (192)	13.4 (5.1)	7.34 (4.3)	6.4 (3.1)	2.8 (3.6)	2.7 (2.1)	10.8 (4.5)	8.3 (4.9)	320 (210)
Return-sweep regressions	86	368 (198)	16.8 (6.0)	12.4 (6.3)	4.2 (2.3)	3.1 (2.6)	4.2 (2.9)	13.1 (5.1)	9.9 (4.6)	331 (213)
Undersweep	1089	163 (59)	17 (5.1)	14.9 (4.8)	2.2 (1.4)	2.8 (3.5)	7.3 (3.2)	10.4 (4.3)	7.8 (5.0)	353 (226)

4.4.3. Modulation of the EVS by Fixation Durations before and after the Return-sweep Saccade

The linear mixed model (LMM) for fixation duration results is shown in Table 4.4 and illustrated in Figure 4.2. These results show that as the EVS increases, so do intra-line fixation durations. Regarding the fixation type effect, compared to intra-line fixations, line-final fixations were significantly shorter ($d=0.03$)⁵, accurate line-initial fixations were significantly greater ($d= 0.59$), and undersweep fixations were significantly shorter ($d= -1.21$). Additional covariates of frequency and word length exerted significant influences where higher frequency words elicited decreased fixation durations and longer words elicited decreased fixation durations. The length effect found differs from the typical length effects in adults. However, it is consistent with length effects on first fixation durations for developing readers where longer words receive multiple fixations

⁵ The effect size is showing that on average line-final fixations were longer than intra-line fixations

hence are typically shorter compared to short words which receive fewer and longer fixations (Tiffin-Richards & Schroeder, 2015b). There was, however, an interaction between frequency and length as the frequency effect was greater for long words compared to short words.

Importantly, we found significant interactions between the EVS and the fixation types. While a larger EVS led to increased fixation durations for intra-line fixations, this effect was greater for line-final and undersweep fixations. However, the EVS effect was similar for accurate line-initial fixations and intra-line fixations. Finding that undersweep fixation durations were influenced significantly by the EVS was surprising, we explore this further in the next section.

Table 4.4. LMM Analyses Showing Log-transformed Fixation Durations as a Function of the Spatial EVS at Fixation Onset and Fixation type

Fixed effects	<i>b</i>	<i>SE</i>	<i>t</i>	<i>p</i>
(Intercept)	2.4651	0.0095	259.8341	<0.01
Onset EVS	0.0204	0.0031	6.6796	< 0.01
Line-final	-0.0249	0.0069	-3.6237	< 0.01
Accurate	0.1637	0.0111	14.7454	< 0.01
Undersweep	-0.2972	0.0111	-26.8605	< 0.01
Fixated word frequency	-0.0193	0.002	-9.7225	< 0.01
Fixated word length	-0.0285	0.002	-14.0213	< 0.01
Onset EVS*Line-final	0.0727	0.0102	7.1016	< 0.01
Onset EVS*Accurate	-0.0011	0.0175	-0.0643	0.9488
Onset EVS*Undersweep	0.0395	0.0128	3.0821	0.0021
Fixated word Freq * Fixated word Len	-0.0114	0.0016	-7.0956	< 0.01
Random effects	Var.	SD	Corr.	
Item intercept	0.0001	0.0105		
Participant intercept	0.0044	0.0660		
EVS slope	0.0004	0.1871	0.76	
Residual	0.0426	0.2063		

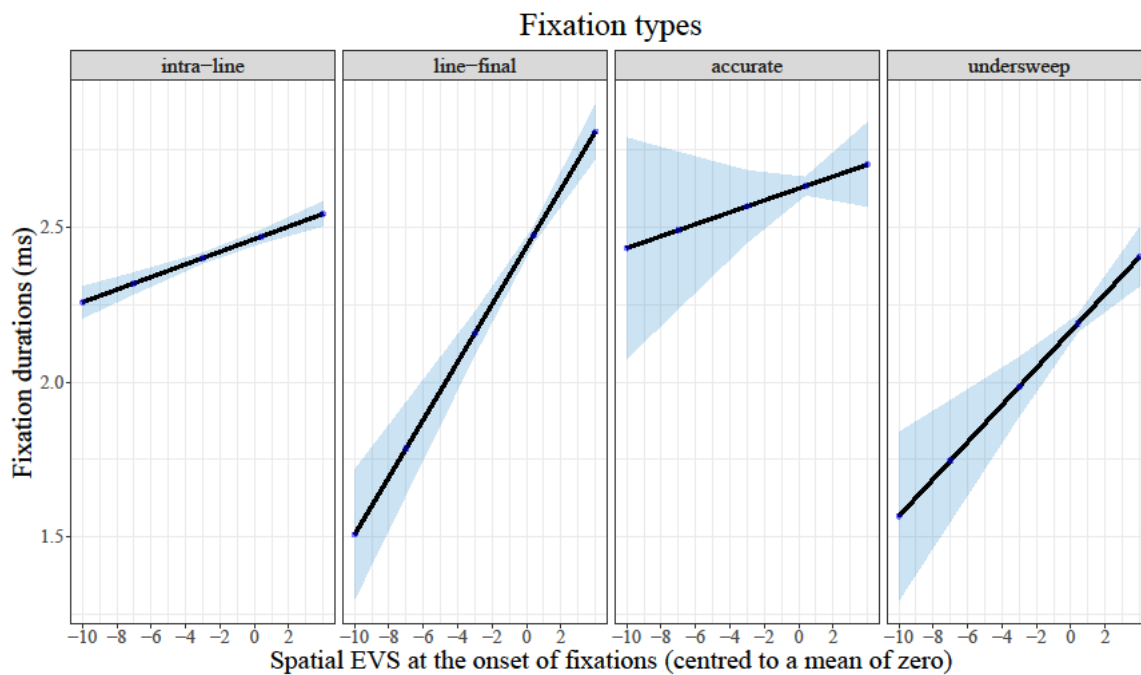


Figure 4.2. Line effect plots showing the interaction between EVS and fixation type for log-transformed fixation durations. Larger EVS indicates wider eye distance ahead of the voice and smaller values indicate smaller EVS. Shading shows ± 1 SE.

4.4.4. Post-hoc Analysis of the EVS Effect on Undersweep Fixations

Previous work has shown that the farther away from the target a primary saccade lands, the quicker a corrective saccade is programmed (Becker, 1972; Becker, 1989; Kapoula & Robinson, 1986). Therefore, we explored the EVS effect on undersweep fixation durations while controlling for the landing positions from the left margin where the undersweep fixation landed in Table 4.5. Although the EVS at the start of the undersweep fixation dependent on the landing position, they are only moderately correlated (0.63). This moderate correlation is because the size of the EVS is also dependent on where the voice is. There was a main effect of the EVS at the start of the undersweep fixation on undersweep fixations where larger spans at the start of an undersweep fixation led to longer fixation durations. There was also a main effect of landing position in the expected direction. Undersweep fixations that landed farther from the left margin had shorter latencies than those closer to the margin. Interestingly, there was an EVS-landing position interaction, where the EVS effect was more pronounced for undersweep fixations that landed further away from the left margin (see Figure 4.3).

Table 4.5. LMM Analyses Showing Log-transformed Undersweep Fixation Durations as a Function of the EVS at the start of Undersweep Fixation and Landing Positions of Undersweep Fixation

Fixed effects	<i>b</i>	<i>SE</i>	<i>t</i>	<i>p</i>
(Intercept)	2.1913	0.0087	253.2088	<0.01
EVS	0.0236	0.0065	3.6201	0.001
Landing position	-0.0464	0.0077	-6.0160	<0.01
EVS*Landing position	0.0107	0.0022	4.8120	<0.01
Random effects	Var.	SD	Corr.	
Item intercept	0.0002	0.0130		
Participant intercept	0.0030	0.0545		
EVS slope	0.0070	0.2641	0.57	
Landing position slope	0.0014	0.0381	-0.60	-0.84
Residual	0.0083	0.0909		

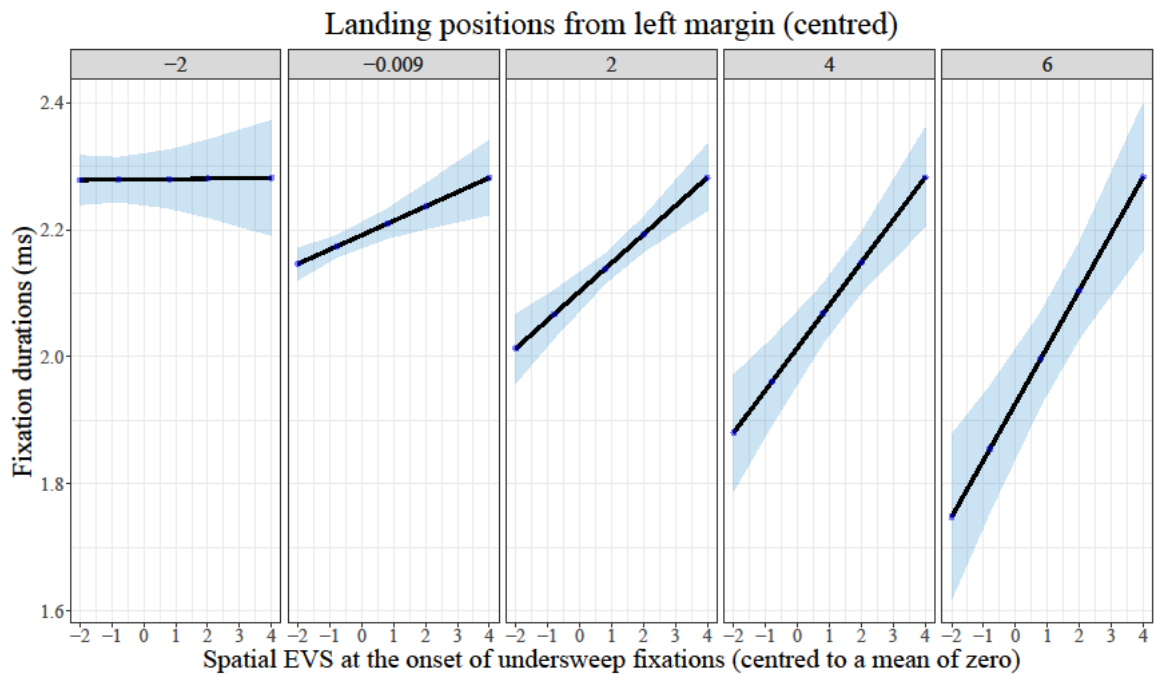


Figure 4.3. Line effect plots showing the interaction between EVS and landing position for log-transformed undersweep fixation durations. Shading shows ± 1 SE.

4.4.5. The EVS and Return-sweep Targeting

To examine whether the EVS influences return-sweep targeting processes, we present the linear mixed model (LMM) results for landing positions and corrective saccade

probability after the return-sweep as a function of the EVS before the return-sweep is launched (line-final offset EVS) in Table 4.6. Contrary to our prediction, the results show that larger EVS at the end of the line-final fixation led to rightward shifts in landing position, but this effect was not significant. However, there was a significant interaction with launch distance where the line-final offset EVS led to a leftward shift in landing positions only for launch distances closer to the left margin (see Figure 4.4). Furthermore, there was a main effect of launch distance on landing positions and corrective saccade probability where return-sweeps that were launched farther from the left margin landed farther from the left margin and led to more corrective saccades (see Figure 4.5). There was a marginal effect of the line-final offset EVS on corrective saccade probability, where a larger EVS led to fewer corrective saccades. These effects were qualified by marginal interaction between line-final offset EVS and launch distance on corrective saccade probability. The line-final offset EVS effect was greater for closer launch distances. Corrective saccade probability was greater as launch distance from the left margin increased, but this only occurred for larger line-final offset EVSs.

Table 4.6. (G)LMM Analyses Showing Landing Positions and Corrective Saccade Probability as a function of Line-final Offset EVS and Launch distance

Fixed effects	Landing Position				Corrective saccade probability			
	<i>b</i>	<i>SE</i>	<i>t</i>	<i>p</i>	<i>b</i>	<i>SE</i>	<i>z</i>	<i>p</i>
(Intercept)	5.288	0.261	20.296	<0.01	0.512	0.141	3.626	<0.01
Offset EVS	0.074	0.135	0.551	0.583	-0.177	0.091	1.943	0.052
Launch distance	0.527	0.130	4.042	<0.01	0.423	0.096	4.392	<0.01
Offset EVS *								
Launch distance	0.097	0.040	2.438	0.016	0.060	0.033	1.820	0.069
Random effects	Var.	SD	Corr.		Var.	SD	Corr.	
Item intercept	0.278	0.527			0.075	0.274		
Launch distance					0.033	0.181	0.62	
Participant								
intercept	2.807	1.675			0.715	0.846		
Offset EVS	0.072	0.268	0.10					
Residual	9.521	3.086						

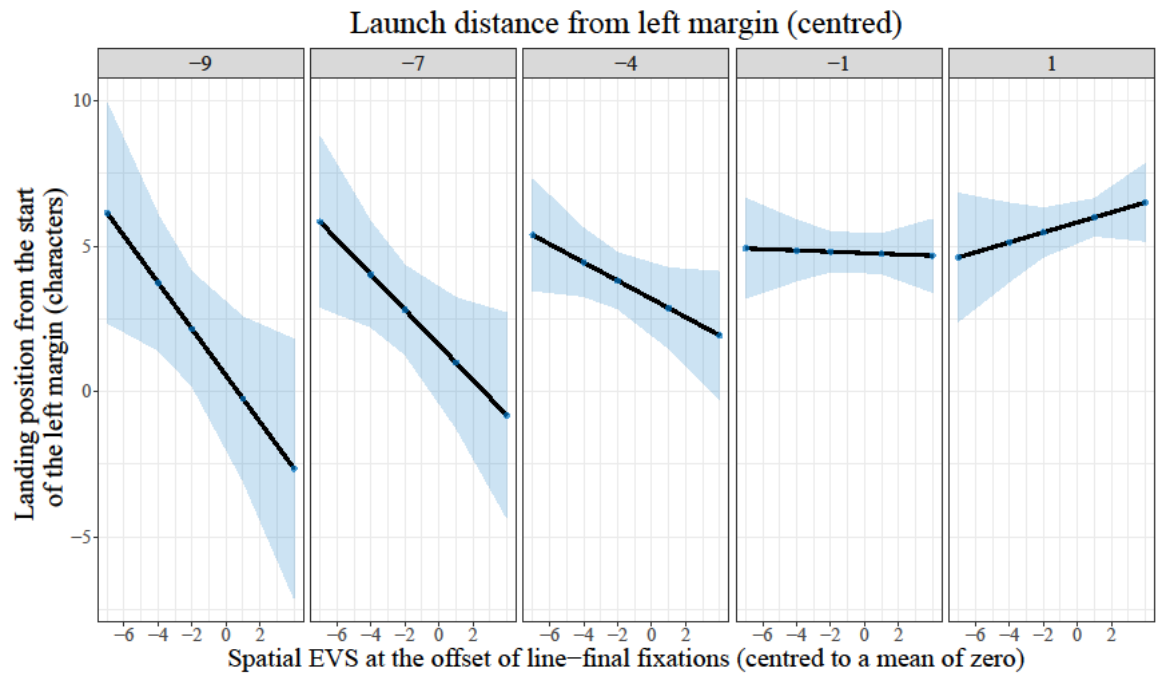


Figure 4.4. Line effect plots showing marginal interaction between the EVS at the end of line-final fixations and launch distance from the left margin for return-sweep landing positions. Shading shows ± 1 SE.

4.4.6. The EVS and Articulation Rates

Finally, we examined whether the EVS is modulated through articulatory mechanisms. We present the linear mixed model (LMM) results for articulation rate using phonemes per second for each word as a function of the EVS at the start of word articulation and word position in a line i.e., intra-line word, line-final word, and line-initial word in Table 4.7. Line-final words are the final words on the first line while line-initial words were the first words on the second line. Every other word was classified as intra-line words with the exception of trial-initial and trial-final words (10.51%) which were excluded as these words are not intra-line words and would confound line-final and line-initial words around the line boundary. Intra-line words were chosen as the baseline for comparison using a treatment contrast.

There was a main effect of the EVS at the start of word articulation on articulation rate as measured by phonemes per second. A large EVS was followed by faster articulation rates. A word position effect was found where words at the line-initial region were spoken faster than words within the line. There was also a main effect of word frequency where more frequent words were articulated faster than less frequent words.

However, there was no interaction between the position of the word in the line and EVS on articulation rates. That is, the EVS effect on articulation rates was the same for all words regardless of their position in the line.

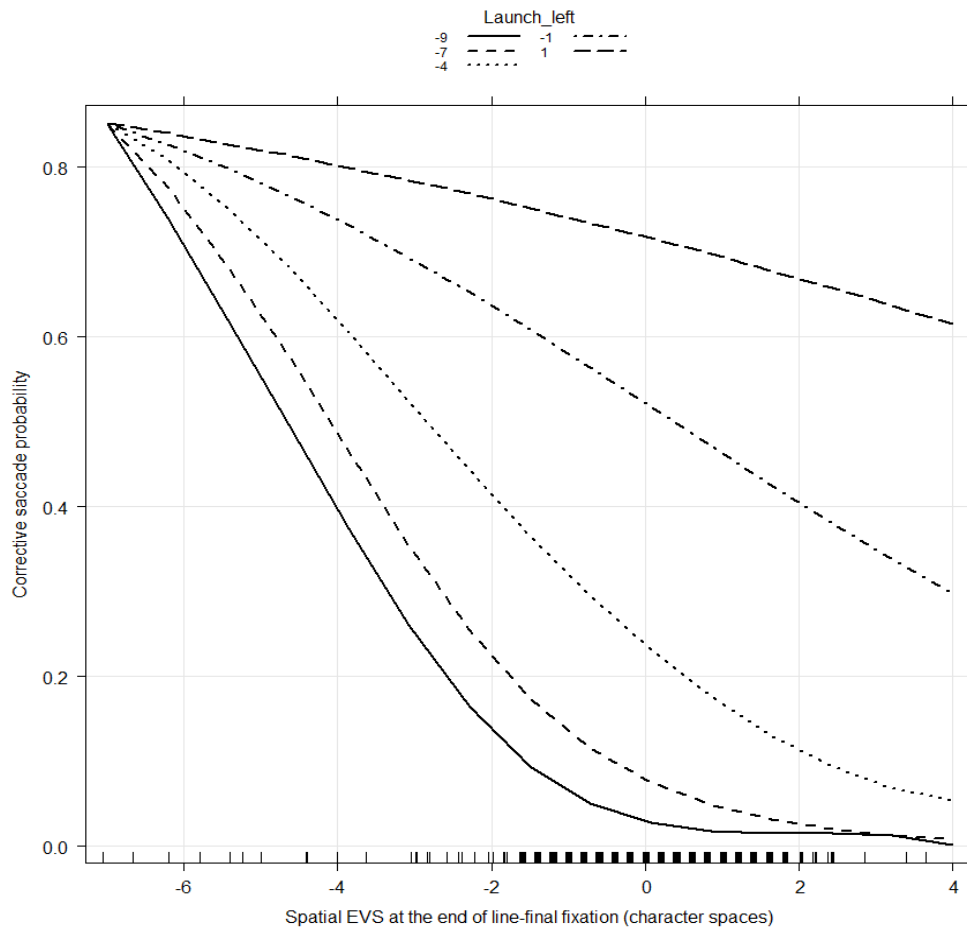


Figure 4.5. Corrective saccade probability as a function of spatial EVS at the end of the line and launch distance from the left margin.

Table 4.7. LMM Analyses Showing Articulation Rates as a Function of EVS at the Onset of Articulation and Word Position on the Line

Fixed effects	<i>Articulation rate (Phonemes per second)</i>			
	<i>b</i>	<i>SE</i>	<i>t</i>	<i>p</i>
(Intercept)	0.9866	0.0095	104.3342	<0.01
Onset EVS	0.0566	0.0051	11.111	<0.01
Intra-line vs Line-final	0.0017	0.0045	0.3692	0.712
Intra-line vs Line-initial	0.0114	0.0042	2.7071	0.0068
Frequency	0.0324	0.001	31.1021	<0.01
Onset EVS* Intra-line vs Line-final	0.0077	0.005	1.5414	0.1232
Onset EVS* Intra-line vs Line-initial	0.0003	0.005	0.0549	0.9562
Random effects	Var.	SD	Corr.	
Item intercept	0.0004	0.0204		
Participant intercept	0.0042	0.0651		
Onset EVS slope	0.0012	0.0350	-0.54	
Residual	0.0250	0.1580		

4.5. Discussion

This study reports data describing the EVS within and between lines using an eye movement corpus of children reading aloud. We assessed the relative impact of the EVS on different fixation populations, return-sweep targeting (i.e., return-sweep landing positions and corrective saccade probability), and articulation rates. Our main finding was that the EVS strongly impacted line-final and undersweep fixations more than intra-line fixations. We discuss this and other findings below.

The average reader's EVS at the start of a fixation was numerically smaller within the line (intra-line fixation) compared to the start (accurate line-initial fixation) and end (line-final fixation) of the lines. This finding contrasts with earlier research with skilled readers, where the EVS at the end of lines was similar to the average EVS at all fixations (Fairbanks, 1937). However, Fairbanks (1937) distinguished between fixations resulting from left to rightward saccades and fixations from right to leftward saccades (i.e., regressions). Regressive movements are common in children (Vorstius et al., 2014) and during oral reading (Anderson & Swanson, 1937). This may account for reduced EVS for intra-line fixations. In the current data, excluding fixations resulting from regressive movements led to numerically similar EVS for intra-line, line-final and accurate line-initial fixations which would be consistent with Fairbanks (1937). However, we kept regressive fixations in because excluding them did not alter our main analysis (see [Appendix C](#) for EVS descriptive statistics without regressive fixations). Our findings

support Fairbanks (1937), who found that the EVS after the return-sweep is significantly longer than average EVS for all fixations. In addition, we specify that this is primarily due to undersweep fixations, i.e., return-sweep saccades followed by a leftward saccade, rather than accurate line-initial fixations. Larger EVS for undersweep fixations occur because of their tendency to land further from the left margin. Critically, the amount of change in EVS from fixation onset to fixation offset was greater for accurate line-initial fixations than for other fixation populations, primarily reflecting the duration of respective fixations (i.e., longer durations provide more time for the voice to catch up).

Eye movements between lines have mainly been studied in silent reading. From these studies, we know that the last fixation on the line is significantly shorter than fixations within the line for adults and children (Abrams & Zuber, 1972; Hofmeister, 1998; Parker, Nikolova, et al., 2019; Parker, Slattery, et al., 2019). In Chapter 1 of this thesis, Adedeji et al. (2021) found only a marginally greater oral reading cost for line-final fixations (33ms) compared to intra-line fixations (32ms), suggesting that the adult readers may have slowed down a bit before the return-sweep saccade was executed during oral reading. In the current Chapter, line-final fixations were 6ms longer on average than intra-line fixations for developing readers. The effect size for this difference was minimal ($d = 0.03$), indicating limited practical significance. However, we observed the typical line-final decrease in fixation durations in the LMM analysis, controlling for between-item and between-subject variance, spatial EVS, word length and frequency, and skewed fixation duration distribution (log-transformation). A by-subject plot of the data showed that some readers exhibited speed-up effects while others did not (see Figure C2). Further examination of this pattern by including an interaction between fixation type and grade level in the fixation durations model showed a difference in the speed-up effect between grades four and five. Only grade five children sped up at the end of the line (see Figure C3). This pattern is consistent with data from German children in grade two who showed no line-final speed-up effects in gaze duration compared to the same children in grade three and adults (Tiffin-Richards & Schroeder, 2018). Interestingly, speed-up effects were found in grade three children (8-year-olds) during silent reading (Tiffin-Richards & Schroeder, 2018) but not in our grade four children (8-year-olds) in this oral reading study. Hence, oculomotor efficiency in planning return-sweeps (Kuperman et al., 2010) and/or parafoveal processing capacity (Rayner, 1977) may be disrupted by oral reading. Therefore, line boundaries may be more disruptive for younger children reading aloud. More research is required to disentangle developmental and individual differences in line-final speed-up effects during oral and silent reading.

Accurate line-initial fixations showed a different pattern from previous developmental return-sweep research. In silent reading, children exhibited no statistical differences between accurate line-initial and intra-line fixations (Parker, Slattery, et al., 2019). This pattern indicates that children's reliance on foveal processing at the start of the line is similar to intra-line reading. However, in this oral reading study, accurate line-initial fixations were significantly longer than intra-line fixations, similar to findings in skilled silent reading (Hofmeister, 1998; Parker, Nikolova, et al., 2019; Parker & Slattery, 2021; Parker, Slattery, et al., 2019; Rayner, 1977). In skilled oral reading, parafoveal processing is reduced (Ashby et al., 2012) and/or delayed (Inhoff & Radach, 2014). Assuming the same relationship exists for children's oral reading, there should be no difference between accurate line-initial and intra-line fixations due to an overall decrease in parafoveal processing. Therefore, finding a significant difference may well be attributed to the coordination of the EVS. Figure C2 in the Supplementary Materials clearly illustrates that this effect was reliable across all children. Comparing the line-final and accurate line-initial fixations indicates that line-final fixation durations may offer further insights into individual differences in oculomotor and linguistic processing at line boundaries.

This research confirms previous work in skilled reading by replicating EVS effects on fixation durations in developing readers (Inhoff et al., 2011; Laubrock & Kliegl, 2015). When comparing one participant's average EVS to another's, a wide average EVS should be associated with shorter average fixation durations. However, using a mixed modelling approach to examine how the EVS of a given participant influences and is influenced by oculomotor and articulatory behaviour, a wide EVS is associated with longer fixation durations. We extend this evidence by showing for the first time that this relationship is greater for line-final and undersweep fixations. Kuperman et al. (2010), Parker, Slattery, et al. (2019) and (Hofmeister, 1997) suggest a parsimonious explanation for the termination of line-final fixations: that these fixations serve to plan return-sweep saccades and may not be as heavily involved in linguistic processing. In line with our predictions, the stronger relationship between EVS and line-final fixations than intra-line fixations may be due to a process monitoring mechanism that aims to ensure a manageable EVS before making a costly return-sweep (Adedeji et al., 2021; Levasseur et al., 2006). Essentially, developing readers may have found it necessary to ensure the voice catches up with the eyes before making return-sweep movements. We suggest the possibility that cases where the span is not sufficiently reduced before the initiation of the return-sweep bear the risk of return-sweep regressions to the line-final position. Indeed, we found that

such cases of return-sweep regressions, while rare, were associated with having more words left to articulate on the prior line.

In Chapter 2, Adedeji et al. (2021) found a significant reading aloud cost of longer fixation durations in oral reading compared to silent reading for accurate line-initial fixations compared to intra-line fixations. Therefore, we expected that fixation durations would be driven by larger EVS much more for accurate line-initial fixations than for intra-line fixations. However, this was not the case; the EVS impacted intra-line and accurate line-initial fixations in the same way. This discrepancy could arise from sampling differences between the two studies. Participants in Adedeji et al. (2021) were skilled readers, while participants in this study were developing readers. Developing readers may be more likely to reduce span before making a return-sweep saccade compared to skilled readers who may prefer to synchronise their eyes and voices much later across line boundaries due to their larger working memory capacity. However, such comparison would need to be investigated further. This proposition queries whether the modulation of the EVS at the line-final fixation or the accurate line-initial fixation is dependent on reading skill.

Surprisingly, undersweep fixations were affected by the EVS. This effect was unexpected as undersweep fixations have been assumed to be terminated based on oculomotor error-correcting mechanisms and not by higher-level cognitive factors (Becker, 1972; Becker & Fuchs, 1969; Hofmeister, 1997). Finding that the EVS effect was present and greater for undersweeps than intra-line fixations is puzzling. Therefore, we modelled the interaction between spatial EVS and landing positions of undersweep fixations to explore this. Existing research shows that the time to correct an undershoot error decreases the farther away from the target the undershoot is (Becker, 1972; Becker, 1989; Fischer et al., 1993; Ohl et al., 2011). This finding has been confirmed for corrective saccades during reading (Slattery, Parker & Vasilev, in preparation). Our investigations were consistent with this hypothesis, except that for large EVSs, the fast-error-correction mechanism for return-sweep saccades that landed far from the target was inhibited. Notwithstanding the moderate correlation between landing position and the EVS, the data reveals that the EVS has an influence on fixations that landed far away from their targets.

The EVS seems to have an influence on all fixation types. The coordination between perception and production during oral reading is likely driven by general cognitive processes such as working memory (Kubler et al., 2022) rather than specific language processes. Buswell (1920) proposed that the EVS and linguistic skills are both driven by

attentional/memory processes rather than one being the effect or cause of the other. Thus, while the EVS is related to linguistic skills, it is also related to high-order working memory processes, which drive even basic oculomotor processes (i.e., undersweep fixations). This proposition aligns with a cognitive control account of the initiation of corrective saccades (Ray et al., 2004) and the influence of working memory on eye movement behaviour (Loh et al., 2022; Luke et al., 2018). Additionally, it is plausible that this coordinative mechanism may be more evident for fixations with greater involvement in oculomotor planning and correction (i.e., line-final and undersweep fixations).

During intra-line reading, the EVS also impacts the length of forward saccades (Inhoff et al., 2011). Saccades are shorter following large EVSs compared to small EVSs. Therefore, we examined whether such effects exist for return-sweep landing positions and corrective saccade probability. We did not find a main effect of line-final EVS on landing position. However, there was a main effect of launch distance on landing positions confirming previous return-sweep studies (Adedeji et al., 2021; Vasilev et al., 2021). Farther launch distances from the left margin resulted in rightward landing positions from the left margin. Interestingly, the main effect of launch distance was qualified by an interaction between line-final EVS and launch distance (see Figure 4.4). An EVS effect on landing positions was found only for return-sweeps launched closer to the left margin. The target of the return-sweep saccade lies in the periphery. However, readers who launch their return-sweep from closer to the left margin are more likely to have their return-sweep target closer to parafoveal regions than launching it from a greater distance. Thus, readers may use this cue to ensure that the amount of information in working memory is not too great. In contrast, this mechanism may not be available for farther launch distances. Due to the small sample of return-sweep data, definite conclusions cannot be made.

Making a corrective saccade depends on global text and linguistic ability (Molina et al., 2020; Parker & Slattery, 2021; Trauzettel-Klosinski et al., 2010). Oral reading also leads to more corrective saccades than silent reading (Adedeji et al., 2021). Therefore, we expected a larger EVS at the end of the line-final fixation to result in more corrective saccades, as greater demand on working memory may interfere with oculomotor precision around line boundaries. We found a marginal main effect of line-final offset EVS on corrective saccade probability in the opposite direction. Larger spans resulted in fewer corrective saccades. There was also a reliable main effect of launch distance corrective saccade probability in line with previous research (Adedeji et al., 2021; Vasilev et al.,

2021). However, a marginal interaction between launch distance and line-final offset EVS indicated that the EVS modulated corrective saccade probability only for closer launch distances, similar to the landing position finding. However, why the line-final offset EVS effect is in the opposite direction from our predictions is less clear. We envisage that the relationship between the EVS and reading ability could be a potential explanation because fewer corrective saccades are associated with better reading (Parker & Slattery, 2021) and larger EVSs with better reading (De Luca et al., 2013; Fairbanks, 1937). However, using an LMM that controls the between-participant variability makes this account less likely. A parsimonious explanation could be that a larger EVS may make readers less likely to land away from the left margin, reducing the probability of initiating a corrective saccade. This explanation also corroborates the landing position interaction results.

The final part of our study sought to provide evidence for modulation of the EVS by articulatory mechanisms. Indeed, we found that when the EVS was large at the onset of word articulation, the rate of articulation of each word measured by phonemes per second was higher than when the EVS was smaller after controlling for the frequency of the to-be-articulated word. These findings support Fairbank (1937), indicating that both speech and oculomotor processes actively and jointly influence the width of the EVS. Additionally, more frequent words were also articulated faster. However, there was no evidence of a difference in EVS modulation by the voice at line boundaries.

In summary, the findings from the current study extend previous evidence and provide new insights into the EVS. First, similar line-final and intra-line fixation durations for younger readers in grades three and four and longer accurate line-initial fixation compared to intra-line fixations for all children, suggest that oral reading impacts saccade initiation at line boundaries. Second, the EVS effect on eye movement behaviour indicates high-level cognitive influence beyond linguistic factors, which was more pronounced at line boundaries, likely due to the costly nature of return-sweeps. Finally, increases in articulation rates due to a large EVS suggest that this high-level cognitive influence impacts post-lexical speech production processes. To conclude, the presence of double costs, i.e., eye-voice coordination and return-sweep movements, for children who primarily read aloud is justification for more research on how such coordinative processes contribute to overall reading performance. Exactly how this modulation changes with development and reading skill appears to be a promising line of inquiry and should be the subject of future research.

4.6. Chapter Overview

Our hypothesis regarding greater costs around return-sweeps (Chapter 2) was confirmed in this Chapter. First, line-final speed-up effects were minimal and limited to only grade five children indicating that younger readers may have found movements across line boundaries more taxing compared to within line movements during oral reading. Second, fixation durations at the start of the line, i.e., accurate line-initial fixations were longer than intra-line fixations contrasting previous silent reading research in children (Parker, Slattery, et al., 2019). We suggest that this increase is also due to a coordination of eye movements and voice output at the start of the line. Third, and crucial to this Chapter was the interaction between fixation type and the EVS. Previous research shows that one way a reader regulates their EVS is through increases in fixation duration. We replicated this in children and found that line-final fixations were more impacted by EVS modulation compared to intra-line fixations, confirming our initial hypothesis of greater costs around return-sweeps during oral reading.

In the next Chapter, we examined the EVS between different readers using an individual differences approach. Based on our findings, so far, we wanted to examine reading-related skill differences in the EVS (Chapter 3) as well as its modulation (Chapter 4).