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. However, most of this research comes from skilled adult readers reading single line sentences. Fifty-one Children in Year three, four and 52 adults read short passages spanning two lines while their eye movements and voices were simultaneously recorded. We examined changes in the EVS within the line and at line boundaries; and the differential effect of the EVS on fixation durations by comparing fixations adjacent to the return-sweep (line-final and line-initial fixations) to intra-line fixations. In addition, we explored whether articulation rates increase when the EVS was large. The EVS showed a non-linear pattern within the line with a decrease towards the end of the line. We replicate the increase in fixation duration due to a large EVS for intra-line fixations, this effect was significantly greater for line-final fixations across all readers. These 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. Importantly, 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.

Keywords: eye-voice span, oral reading, return-sweeps, children

1. Introduction

Oral reading is a complex task that involves the coordination of oculomotor, lexico-semantic, and articulatory processes (Godde et al., 2021; Inhoff & Radach, 2014; Kim et al., 2019). Oral reading is typically the default way in which children first learn to read. However, because they have not yet acquired efficient word recognition skills, children often struggle to produce fluent speech while simultaneously comprehending the text (Blythe & Joseph, 2011; Reichle et al., 2013; Vorstius et al., 2014). When reading aloud, fixation durations are typically longer, and saccades are shorter compared to silent reading (Rayner, 2009). One reason these differences exist is because, when reading aloud, the eyes scan information much faster than words can be articulated, so the eyes are typically ahead of the voice . This lag or distance is known as the *eye-voice span* (EVS). The EVS was documented in the early days of eye movement research (Buswell, 1920), but there has been renewed interest in the topic more recently (Laubrock & Kliegl, 2015; Silva et al., 2016). The EVS is often considered a proxy for working memory, such that when the EVS is too large, more processing demands are placed on working memory (Geyer, 1967; Laubrock & Kliegl, 2015; Pan et al., 2013). As a result, the oculomotor system slows down to reduce the uptake of new information, freeing memory capacity and giving articulatory processes time to catch up (Inhoff et al., 2011; Laubrock & Kliegl, 2015). This slowing down leads to an increase in fixation durations during oral reading.

While many of the basic properties of the EVS have already been well documented, a few questions remain unanswered. First, it is not well understood how the EVS changes as readers progress through a line of text. Second, it is currently not clear how readers modulate their EVS at line breaks- when they must make a long eye-movement (return-sweep) to the next line of text. Such long eye-movements are crucial for progressing through the text, but they also present a potential challenge in the sense that the eyes could get too far ahead of the voice. It is currently unknown how the EVS may change at line breaks. Finally, it is not well understood how the EVS changes with reading development. While (Buswell, 1920) seminal work presented an early analysis of developmental trends, few studies using modern equipment have addressed this question. Ultimately, understanding eye-voice coordination is crucial for any theory that seeks to explain how children first learn to read. In the present study, we tested how the EVS changes with reading development in a sample of children in Year three, four and five, as well as a control group of adult readers. Additionally, we examined how the EVS changes as readers progress through a line of text and what changes, if any, occur in the EVS as readers make a return-sweep to a new line of text.

The Relationship between Eye Movements and the EVS

Eye-movements have mostly been studied during silent reading. However, there are differences when reading a text aloud. More generally, reading fixations are longer, regressions are more frequent, and saccade lengths are shorter during oral compared to silent reading in both children and adults (see Adedeji et al., 2021; Anderson & Swanson, 1937; Kim et al., 2019; Krieber et al., 2017; Vorstius et al., 2014). Linguistic effects commonly observed in silent reading, such as word frequency, are reduced in oral reading (Vorstius et al., 2014). Additionally, there is a reduction in the perceptual span during oral reading– which is 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 in reading modality occur because the rate of spoken language (~ 150 words per minute [WPM]) is typically slower than silent reading rates (250 WPM; Brysbaert, 2019). There is also evidence that phonological information may be processed earlier during oral reading compared to silent reading, due to the need to articulate words (Pan et al. 2016). Therefore, speech production during oral reading constrains the nature of information processing and further limit how far ahead of the voice the eyes can go (Kim et al., 2019; Levin & Addis, 1979).

For skilled readers, whose efficient lexical skills enable them to quickly progress through the text, there is a tendency for the voice to trail behind the eyes (Vernon, 1931). This lag results in the widening of the EVS. This is necessary for fluent reading, in the sense that readers can plan expressiveness and rhythm based on punctuation and sentence structure (Buswell, 1920). As reading skill develop, readers begin to expand their EVS from approximately eight character-spaces in seven year olds to around 15 character-spaces in adulthood. Although no study to date has examined the association between working memory and the EVS, Buswell (1920) first speculated that the width of the EVS correlates with the attentional capacity to hold multiple words in the mind at a given time.

In Baddeley and Hitch's model of working memory capacity (Baddeley, 2010; Baddeley & Hitch, 2019), phonological information of perceived words is rehearsed in the phonological loop component for later articulation. Due to limited working memory capacity, an overly large EVS can exceed buffering limits in the phonological loop, making unarticulated words prone to errors and forgetting. This can in turn disrupt the normal reading flow as more regressive saccades would be generated (Geyer, 1967). Indeed, an increase in regressions has been associated with lower oral reading rates (Søvik et al., 2000). When the EVS becomes large, Inhoff et al. (2011) and Laubrock and Kliegl (2015) show that single fixation durations, refixations and regressions increase to hold back the eyes, thus reducing the rate of new visual input and linguistic processing.

No study to date has tested whether the same pattern of results also occurs in children. However, there is evidence that the perceptual span in children can be modulated by increased working memory load from less frequent words (Meixner et al., 2022). This suggests that a similar modulation of the EVS to that of adults may also be observed in developing readers, though this remains to be tested. Such dynamic modulation of the EVS would demonstrate how domain-general cognitive processes such as working memory can directly influence oculomotor control (Luke et al., 2018). Furthermore, this mechanism can be understood as delaying the rightward shift of attention once lexical access is completed for the current word, as would be predicted by the E-Z Reader model of eye movement control (Inhoff et al., 2011; Reichle et al., 2009). Therefore, the continuous monitoring of the EVS appears necessary to allow readers to make the oculomotor adjustments that are needed to read the text fluently.

The Eye-Voice Span and Multiline Reading

The continuous monitoring of the EVS is especially critical when readers must navigate multiple lines and sentences within a paragraph. The EVS can change both within lines and within sentences. For example, Buswell (1920) found that the EVS is two characters smaller at the end of lines compared to the beginning of lines. Fairbanks (1937), on the other hand, found a much larger difference of 8 characters. Buswell argued for a weak effect of line boundaries on the EVS, whereas Fairbanks attributed the much larger difference to readers making an eye-movement to the next line. The conflicting findings of the two authors may be partly explained by methodology. While Buswell (1920) measured the EVS from the start of each word's articulation to the current fixation location, Fairbanks (1937) measured it from the start of each fixation to the currently articulated character or phoneme. Therefore, although these measurement differences may explain some of the conflicting findings, a more detailed investigation of fixations around line boundaries is necessary. One key feature of multiline reading is that readers need to programme long eye-movements (known as *return-sweep saccades*), which take their gaze from the end of one line of text to the beginning of the next (Huey, 1900). Return-sweeps are thought to target an area close to the left margin rather than word centres like shorter saccades occurring within the same line (Parker & Slattery, 2019; Slattery & Vasilev, 2019; Vasilev et al., 2021). Due to their large amplitude, return-sweep saccades tend to undershoot the line start (Hofmeister, 1998). This leads to short fixations (sometimes called "undersweeps"; Parker et al., 2017), which are then quickly corrected by a leftward saccade approximately 40-60% of the time. Because undersweep fixations often land far away from the left margin, this would also lead to an increase in EVS at the start of the line. Undersweep fixation durations are typically much shorter than both the line-final fixation duration (i.e., fixation immediately before the return-sweep) and the average fixation duration within a line ("intra-line" fixations). Undersweep fixations are thought to be terminated quickly due to retinal feedback from landing in a suboptimal location at the start of the line and to be independent of linguistic processes (Hofmeister et al., 1999; Parker, Nikolova, et al., 2019).

However, research also shows that they provide some processing benefit for words they land on and the line-initial word (Slattery & Parker, 2019). If the initial landing position on the new line is not corrected and readers make a right-ward saccade in the reading direction, these line-initial fixations are sometimes called “accurate” (Parker & Slattery, 2019; Parker, Slattery, et al., 2019). Accurate line-initial fixation durations are typically longer compared to both intra-line and line-final fixations. Line-final fixations, on the other hand, tend to be shorter than intra-line fixations (Adedeji et al., 2021; Parker, Nikolova, et al., 2019; Parker & Slattery, 2021), potentially because they mostly reflect saccadic programming of the return-sweep (Hofmeister, 1998; Parker et al., 2025).

While these findings have been established during silent reading, Adedeji et al. (2021) showed that the difference between line-final and intra-line fixation durations is less pronounced in oral reading. This suggests that the slowdown during line-final fixations may allow the voice to briefly catch up before making the return-sweep saccade. This proposition is consistent with Levin and Buckler-Addis (1979), who suggested that readers may slow down at the end of lines in a similar manner to slowing down at sentence boundaries, leading to a reduction in the EVS at the end of the line. Critically, unlike undersweep fixations, intra-line and accurate-line initial are both thought to be under linguistic and oculomotor control since they are influenced by reading ability and word frequency, whereas undersweeps are not (Kuperman et al., 2010; Mitchell et al., 2008; Parker & Slattery, 2021). The evidence on line-final fixations is somewhat mixed, with some studies suggesting they are primarily influenced by oculomotor processes (Parker et al., 2025) and others implying a combined influence of lexical and oculomotor processes (Parker et al., 2021).

Previous evidence on how sentence boundaries affect the EVS also offers a nuanced picture. Buswell (1920) suggested a stronger effect of sentence boundaries compared to line boundaries, reporting that the EVS was eight-character spaces smaller at the end of sentences. By contrast, Fairbanks (1937) reported only a three-character-space difference. Again, while measurement differences are possible explanations (see Fairbanks, 1937, p. 84), Buswell proposed that the EVS is more related to meaning units (words) than typographic units (line boundaries). Because readers are attempting to grasp the meaning of the text before articulation, they scan ahead creating a larger span at the start of a sentence. At the end of the sentence, readers spend more time integrating the meaning of words before beginning a new thought on the next sentence, thus creating a smaller span. The span still increases at the start of the next sentence because the voice pauses more in response to punctuation, and the eyes have time to scan ahead. In addition to sentence wrap-up effects, Levin and Buckler Addis (1979) proposed that the EVS is also influenced by contextual effects, such as text predictability and the availability of information. Higher predictability due to increased context widens the EVS. This is consistent with the higher skipping probability and shorter fixation durations for highly predictable words (e.g., Ehrlich & Rayner, 1981). It is important to state that sentence and line boundaries often overlap. Therefore, increasing predictability as information accumulates toward the end of the line suggests that the EVS may be modulated within lines just as much as it is modulated within sentences. Taken together, the limited and somewhat outdated evidence provides an incomplete understanding of EVS co-ordination during multiline reading. It is possible that the reported changes in EVS within lines and within sentences depend on the specific measures utilised. Any study that attempts to clarify these patterns must account for the confounding effects of sentence and line boundaries. Although this is not the primary focus of the present investigation, it underscores the complexity of EVS dynamics and the need for methodological precision in future research.

Children's Multiline Reading

We next consider how eye-movements of developing readers are affected by line and sentence boundaries. Children's eye movements during both silent and oral reading appear to be more disrupted by line boundaries compared to those of skilled readers. In a longitudinal silent-reading study, Tiffin-Richards and Schroeder (2018) found that Grade 2 children (equivalent to

UK Year 3) did not exhibit speed-up effects for line-final words, but these effects emerged by the time these children reached Grades 3 and 4. Additionally, children often initiated regressions at line-final words rather than at clause- or sentence-final words, which is more typical of skilled readers. This indicates that line boundaries become functionally equivalent to sentence boundaries for less experienced readers or when cognitive demands increase, as is the case with oral reading. Consistent with this, Levasseur et al. (2006) reported that 8 and 9-year-olds were less fluent when reading aloud and more likely to stumble at line boundaries when line and clause boundaries overlapped, compared to a non-overlapping condition. In another silent reading study (van Silfhout et al., 2014), Grade 8 students (~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). This suggests that overlapping line and sentence boundaries are beneficial as reading experience accumulates. These findings underscore the importance of examining how line boundaries affect children's reading fluency, offering a valuable context for understanding the development of oral reading skills.

1.1. The Present Study

Our first objective was to investigate how children's EVS changes within lines, and to compare these changes with those observed in a group of skilled readers. This has only been descriptively presented by a few researchers more than a century ago (Quantz, 1897; Buswell, 1920).Our second objective was to investigate how the EVS changes between lines. To date, this effect has only been documented in skilled readers (Fairbanks, 1937). Building upon the contemporary classification of fixations across line boundaries (Parker et al., 2019), we examined the EVS at line-final, accurate line-initial and undersweep fixations, and compared these to intra-line fixations. This classification allows us to examine eye-voice coordination at locations of greatest mismatch, such as during undersweep fixation (Fairbanks, 1937). Line-final, accurate, and undersweep fixations are all adjacent to the return-sweep saccade. Therefore, if the EVS at these regions differ significantly from intra-line fixations, this would indicate that readers adjust their eye–voice coordination at line boundaries to support more efficient text processing.

Third, we investigated how the EVS influences fixation durations for each fixation type. One reason readers may pause more at line boundaries during oral reading is that they wait for the voice to catch up with the eyes (Adedeji et al., 2021). Moreover, line boundaries are especially costly for developing readers, as they are generally associated with reduced reading fluency compared to skilled readers (Levasseur et al., 2006; Parker, Slattery, et al., 2019; Tiffin-Richards & Schroeder, 2018). Therefore, eye-voice coordination and return-sweep planning may jointly impose greater cognitive processing demands compared to eye-voice coordination alone. If so, we would expect the EVS to affect fixation durations around the return-sweep (i.e., line-final and accurate line-initial fixations) more than it does to intra-line fixations. Modulating fixation durations at the end of the line may be necessary to allow a sufficient reduction in the EVS before making a potentially costly return-sweep to the following line. If readers execute a return-sweep prior to adequately establishing a manageable load in the phonological buffer, they may need to regress to the end of the line, which would likely be more disruptive to the reading process. Such long-distance regressions would likely be more disruptive than typical intra-line regressions. Indeed, regressions to previous lines are less common than intra-line regressions (Ehrlich & Rayner, 1983), suggesting that readers use them infrequently. Additionally, the EVS may strongly modulate readers' accurate line-initial fixations, which may serve as a natural pause allowing the voice to catch up with the eyes before progressing through the new line. These questions are important as Laubrock and Kliegl (2015) reported that the EVS influences single fixation durations more than word length and frequency effects, highlighting its importance for understanding reading aloud. Since undersweeps are generally considered to reflect low-level oculomotor processes (e.g., Hofmeister, 1998), we did not expect these fixations to be affected by the EVS.

Finally, we explored how the EVS is modulated by articulation rates. The EVS is affected by both articulation rate and eye-movement rate. If the eyes speed up or the voice (articulation rate) slows down, the EVS increases; if the eyes slow down or articulation rate speeds up, the EVS decreases. In their seminal work, Fairbanks (1937) recognised this complex dependency, but they never explicitly tested the extent to which articulation rate influences the EVS. Laubrock and Kliegl (2015) largely dismissed this possibility, as they argued that articulation rate is relatively linear throughout the text, with most of the adjustments being made by the eyes. However, as neither study provides empirical data on this issue, we sought to answer this fundamental question about the nature of the EVS. We report data collected data from developing readers (Years 3-5) as they read two-line passages. To compare their performance to adults, we also collected a reference sample of skilled readers[1].

2. Method

This section is partly adapted from Adedeji et al. (2024) because the child data analysed here are a subset of the data collected for a larger project examining children's reading development. The adult data is novel and were collected for this study only.

2.1. Participants

2.1.1. Child Sample

Sixty-four children from two primary schools in Bournemouth, UK participated in this research after school; parental and child consent were obtained. All participants were English monolinguals, except seven who spoke at least one additional language. Results did not differ when these participants were included or excluded; therefore, their data were retained. No children had a prior diagnosis of reading disorders, and all reported normal or corrected-to-

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[1] This study originally consisted only of developing readers. However, we also tested a reference sample of adult readers at the request of anonymous reviewers. We report the data for both samples together for simplicity, but the adult sample was collected after the developmental one.

normal vision. Some participants' data were excluded lost 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 aged 7- 10 years (27 female) were used in the current study. There were 13 children in Year 3 (6 females; Mean_{Age} = 7.8 years; SD_{Age} = 0.5 years), 21 children in Year 4 (13 females; Mean_{Age} = 8.8 years; SD_{Age} = 0.5 years), and 17 children in Year 5 (9 females; Mean_{Age} = 9.9 years; SD_{Age} = 0.4 years). 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; Wechsler, 2006), which confirmed age-appropriate reading levels (*Mean* = 105.51, *SD* = 9.58) and normal verbal 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).

2.1.2. Adult Sample

Fifty-five undergraduate students and staff members from the University of Leicester participated after providing written consent. All participants reported English as their native language (31 were monolinguals and 24 were bilinguals or multilinguals). No participants had a prior diagnosis of reading disorders, and all reported normal or corrected-to-normal vision. Three participants' data were excluded due to technical errors with the audio recording. Therefore, data from 52 participants aged 18–38 years (49 female; Mean_{Age} = 20.55 years, SD_{Age} = 3.80) were used in the current study. Participants completed the Test of Word Reading Efficiency —Second Edition (TOWRE-2; Torgesen et al., 1999; Form A) and Digit Span subtest of the Wechsler's Adult Intelligence Scale —Fourth Edition (WASI-IV; Wechsler, 2008). All participants were naïve as to the purpose of the study and were compensated with either 2 course credits or £10 for their time. The University of Leicester Research Ethics Committee approved the study (ID 42911).

2.2. Materials and Design

The experimental stimuli comprised two sets of 42 passages each; however, each child read only one set (for details, see Adedeji et el., 2023 and Figure 1). This design reflected the initial plan to test participants at two time points, with each participant seeing a different item set at each session. However, due to the Covid-19 pandemic, the second testing session could not be completed. Nonetheless, participants in the adult sample read both item sets. Each passage contained between 70 and 101 characters (*M*= 87.18 characters, *SD*= 8.03) and comprised two sentences spanning two double-spaced, left-justified lines. The first line contained an average of 48 characters and 7 - 12 words; *M*= 9.83 words). The second line contained an average of 38 characters and 4 - 12 words; *M*= 7.73 words). Six-letter target words of one or two syllables were embedded in each passage, but target-word properties were not considered in the current analysis. Target words and sentence frames varied across the two item sets. All 84 passages were assessed for readability using Flesch-Kincaid grade level metric (*M*= 2.36, *SD*= 0.92). Since each child read only 42 passages, their assignment to the two sets was counterbalanced. However, all adult participants read the full set of 84 passages.

Figure 1

An Example Passage

A huge bowl of spoilt fruit was on the table. It
must have been there for days.

2.3. Apparatus

2.3.1. Child Data Apparatus

Eye movement data were recorded with an SR Research EyeLink 1000 plus desktop-mounted eye-tracker at a sampling rate of 1000Hz. Reading was binocular, but only the right eye was recorded (for five participants, the left eye was recorded due to tracking problems with their right eye). Stimuli were presented on a BenQ XL2410 T LCD monitor with a 1920 x 1080 resolution and 60 Hz refresh rate. Participants' voices were recorded using a Fifine USB Microphone (K056 Model) with an approximate latency of 3- 24 ms. A forehead rest was used to minimise head movements; a chin rest was not used to allow unhindered articulation during reading. The passages were presented in black 22-point monospaced Consolas font on a white background. The text was vertically centred on the screen with a 550-pixel horizontal offset. The eye-to-screen distance was 70cm, and each letter subtended ~ 0.34º horizontally. Experimental programming was implemented in MATLAB R2018a (MathWorks) using Psychtoolbox v3.0.11 (Brainard, 1997; Pelli, 1997) and the EyeLink toolbox (Cornelissen, Peters, & Palmer, 2002). The experiment was run on a Windows 7 operating system.

2.3.2. Adult Data Apparatus

The eye movement data were recorded using an SR Research EyeLink 1000 plus tower-mounted eye-tracker with a sampling frequency of 1000Hz. Reading was binocular, but only the right eye was recorded. Stimuli were presented on a BenQ XL2420Z LCD monitor with a 1920 x 1080 screen resolution and 60 Hz refresh rate. Participants' voices were recorded using an XLR Microphone coupled with an M-Audio M-Track 2 X 2 interface, with an approximate latency of 2 – 359 ms. A forehead rest was used to minimise head movements; a chin rest was not used to allow unhindered articulation during reading. The passage was presented in a black 29-point monospaced Consolas font on a white background. The text was vertically centred on the screen with a 550-pixel horizontal offset. The eye-to-screen distance was 80cm, and each letter subtended ~ 0.30º horizontally. Experimental programming was implemented in MATLAB R2023b (MathWorks) using Psychtoolbox v3.0.11 (Brainard, 1997; Pelli, 1997) and the EyeLink toolbox (Cornelissen, Peters, & Palmer, 2002). The experiment was run on a Windows 7 operating system.

2.4. Procedure

Each participant provided written consent and received verbal instructions before the experiment began. Participants were tested in quiet rooms within the school (children) or in the eye-tracking laboratory (adults), where they completed two sessions. In one session, they completed an eye-tracking experiment; in the other, they completed a paper-and-pencil offline assessment of reading and cognitive ability. The order of the sessions differed among the child participants, with some completing the eye-tracking experiment first and others the offline assessment first. All adults completed the eye-tracking experiment 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 the experimenter could terminate the trial. After this, participants completed a 9-point calibration and validation procedure. Validation accuracy was always < 0.40° (visual angle), and recalibration was performed whenever the pre-trial drift check fell below this threshold. Recalibration was also performed after a 2-minute break scheduled in the middle of the experiment.

A 50-pixel black gaze box centred on the first letter of the passage was presented at the start of the trial. As soon as a stable fixation was detected inside the box, it disappeared and the passage was presented on the screen. Three practice trials were completed to familiarise participants with the instructions. During the experiment, participants answered TRUE/FALSE comprehension questions that appeared after 33% of the passages by pressing one of two buttons on a keyboard. Both sessions lasted for approximately 1 hour for the children sample and 40 minutes for the adult sample, with opportunities for a break between sessions.

2.5. Data analysis

EyeDoctor 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. Afterwards, the EMreading R package (Vasilev, 2019) software generated fixation and word-level data for the analysis based on the manually adjusted fixation data. The PRAAT software (Boersma & Weenink, 2019) was used to manually pre-process the audio data. The waveforms, spectrogram and formants were used to determine the onset and offset 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. A custom R script was developed to merge eye fixation data with audio TextGrids and compute Spatial EVS in character spaces either at the onset of each fixation or at the onset of each word's articulation (https://github.com/vadedeji/Multline_EVS). For each fixation, the script identified the phoneme or letter articulated at fixation onset and calculated the distance between the fixated and spoken character. For each articulated word, the script identified the fixation location at the onset of word articulation and calculated the distance between the positions. Since the speech data was segmented by words, we assumed a 1:1 grapheme–phoneme mapping and estimated letter timings by dividing word articulation durations by word length (Laubrock & Kliegl, 2015). Table 1 summarises the measures analysed in the current study.

Table 1

Measures and their Operational Definitions

Measure	Sub-measure	Operational definition
Eye-voice span	at fixation onset	The distance (in character spaces) between the fixation location and the approximate letter/phoneme being uttered at fixation onset.

	at articulation onset	The distance (in character spaces) between the first letter of the articulated word and the fixation location at that time of articulation onset.
Fixation Duration		The duration of individual fixations on a word
Articulation Rates		The number of phonemes uttered per second.
Fixation types	Intra-line	Fixations 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

The result section reports two modelling approaches. First, Generalised Additive Mixed Models (GAMMs) were used to model potentially non-linear effects of relative word position (RWP) on the line for the EVS at articulation onset. In GAMMs, some continuous predictors are specified as smooths that allow the modelling of potentially non-linear relationships. The models were fit with the gam() function from the mgcv package 1.9-3 (Wood, 2017) and visualised with itsadug package v.2.4 (van Rij, Wieling, Baayen, & van Rijn, 2020). A fixed effect of Participant Group was included while smooth terms were added for the effect of RWP on the line, its interaction with Participant Group, by-subject random intercept and slopes, and by item random intercepts and slopes. RWP was measured by dividing each word's position by the total number of words on each line. Smooth terms are captured using estimated degrees of freedom (*edf*), with values greater than 1 indicating increasing non-linearity.

Second, Linear Mixed Models (LMMs) were fitted using the (lme4 package v1.1-21: Bates, Mächler, et al., 2015) in the R software v 4.3.1 (R Core Team, 2020) to analyse the EVS and fixation duration data adjacent to the return-sweep saccade. (lme4 package v1.1-21: Bates, Mächler, et al., 2015). In the LMM 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 until convergence was achieved (Bates, Kliegl, et al., 2015). The results were considered statistically significant if the *p*-values were ≤ 0.05. Fixation Type was treated as a fixed effect, and a treatment contrast coding compared each fixation type (line-final, accurate line-initial, and undersweep) to intra-line fixations. Participant Group was treated as a fixed effect with successive difference contrast which compared Year 4 with Year 3 children, Year 5 with Year 4 children and Adults with Year 5 children. The EVS was included as a predictor centred at 0. Length and frequency of fixated words were included as statistical controls in the fixation and articulation rate models and were also centred at 0 (Kliegl et al., 2006). Because fixation durations and articulation rates were skewed, these measures were log-transformed (untransformed analyses produced similar results; see Supplemental Material). Cohen's *d* effect sizes are reported. In the result section, all reported analyses *exclude* regressive fixations, which tend to reduce the EVS disproportionately.

3.0. Results

All participants demonstrated comprehension accuracy of at least 50%, indicating they read the sentences for meaning (children sample: mean: 84.9%, *SD*: 8%, range: 64.3-100%; adult sample: mean: 92.4%, *SD*: 4%, range: 81.0-100%;). A total of 27.55% of the children's and 22.06% of the adult's fixation-based data were removed due to blinks occurring on or around fixations, fixations outside the 80 – 1000 ms range, and fixations where the corresponding speech data had errors such as substitution, mispronunciations or repetition. The data removed due to articulation errors on individual words or entire trials was 11.87% for children's and 0.46% for adults.

3.1. Descriptive Statistics for EVS, Fixation Duration and Articulation Rate Measures

Table 2 reports descriptive statistics for EVS measures, as well as articulation and fixation durations across participant groups, while Table 3 presents EVS measures for different fixation types.

Table 2

Mean (Standard deviation) for Dependent Measures for each Participant Group. Data from Fairbanks (1937) is added for comparison where available.

Group	Year 3 children	Year 4 children	Year 5 children	Adults	Fairbanks Adults- Good readers	Fairbanks Adults- Poor readers
EVS at Fixation Onset (cs)- all fixations	9.30 (10.33)	9.29 (11.39)	11.00 (13.18)	9.65 (15.90)	14.21	10.69
EVS at Forward Fixation Onset (cs)	12.30 (4.82)	12.9 (4.84)	15.4 (5.31)	14.4 (5.65)	15.32	11.93
EVS at Regressive Fixation Onset (cs)	1.68 (15.28)	1.53 (16.44)	2.97 (18.59)	-2.95 (25.02)	8.53	6.30
EVS at Articulation Onset (cs)	8.11 (6.44)	8.61 (7.71)	10.20 (9.58)	9.19 (10.35)	-	-
Articulation Rate (phonemes/sec)	9.76 (4.87)	9.73 (4.24)	11.50 (4.92)	15.70 (6.03)	-	-
Fixation Duration (ms)	354 (196)	328 (189)	294 (154)	262 (132)	-	-
Gaze Duration (ms)	436 (254)	407 (236)	359 (207)	309 (178)		

Note: cs: character spaces. ms: milliseconds. sec: seconds.

Table 3

Mean and Standard deviation for EVS at Fixation Onset and Offset, and Fixation Duration of each Fixation Type for all Participant Groups

Participant Group	Fixation Type	EVS at Fixation Onset (cs)		EVS at Fixation Offset (cs)		EVS change between Onset & Offset (cs)		Fixation duration (ms)	
		M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Year 3	Intra-line	12.10	4.75	7.89	4.37	4.51	2.74	371	200
	Line-final	12.60	4.48	7.53	4.17	5.23	3.08	390	229
	Accurate	12.50	4.61	6.35	3.92	6.16	2.79	487	184
	Undersweep	16.10	5.31	14.10	5.14	2.12	1.25	158	47
Year 4	Intra-line	12.70	4.80	8.77	4.44	4.30	2.60	344	183
	Line-final	12.80	4.26	8.09	3.74	4.91	2.95	359	200
	Accurate	12.70	4.77	7.29	4.41	5.78	3.15	435	164
	Undersweep	16.50	4.90	14.70	4.69	2.02	1.36	156	61
Year 5	Intra-line	15.20	5.35	10.90	5.27	4.64	2.71	307	158
	Line-final	14.90	4.11	10.40	3.90	4.70	2.94	309	189
	Accurate	15.80	5.33	9.72	4.98	6.23	3.05	395	152
	Undersweep	18.40	4.93	16.00	4.52	2.68	1.57	177	63
Adult	Intra-line	14.20	5.74	9.37	5.52	5.30	2.82	272	135
	Line-final	14.00	4.43	9.33	4.06	4.83	2.79	245	130
	Accurate	15.20	5.76	9.49	6.07	6.11	2.90	320	124
	Undersweep	17.30	5.05	14.70	5.11	2.93	1.64	161	53

Note: cs: character spaces. ms: milliseconds. Regressive fixations were excluded here as they have the tendency to reduce the EVS disproportionately. See supplemental file, Table S1 for data including regressive fixations.

3.2. How Does the EVS at Articulation Onset Change Within Lines?

To answer our first research question of how the EVS at articulation onset changes within lines, we fitted two GAMM models (for the first and second line of text, respectively), using each word's relative position (RWP) on the line as a predictor. In this analysis, the EVS was measured at the start of articulation so that most words in the corpus could be included, allowing for an objective comparison of EVS across different word positions on each line. The GAMM model results are presented in Table 4 and are visualised in Figure 2.

Table 4

GAMM Results showing Modulation of EVS at Articulation Onset by Relative Word Position (RWP) for Line 1 and 2 of the Passage

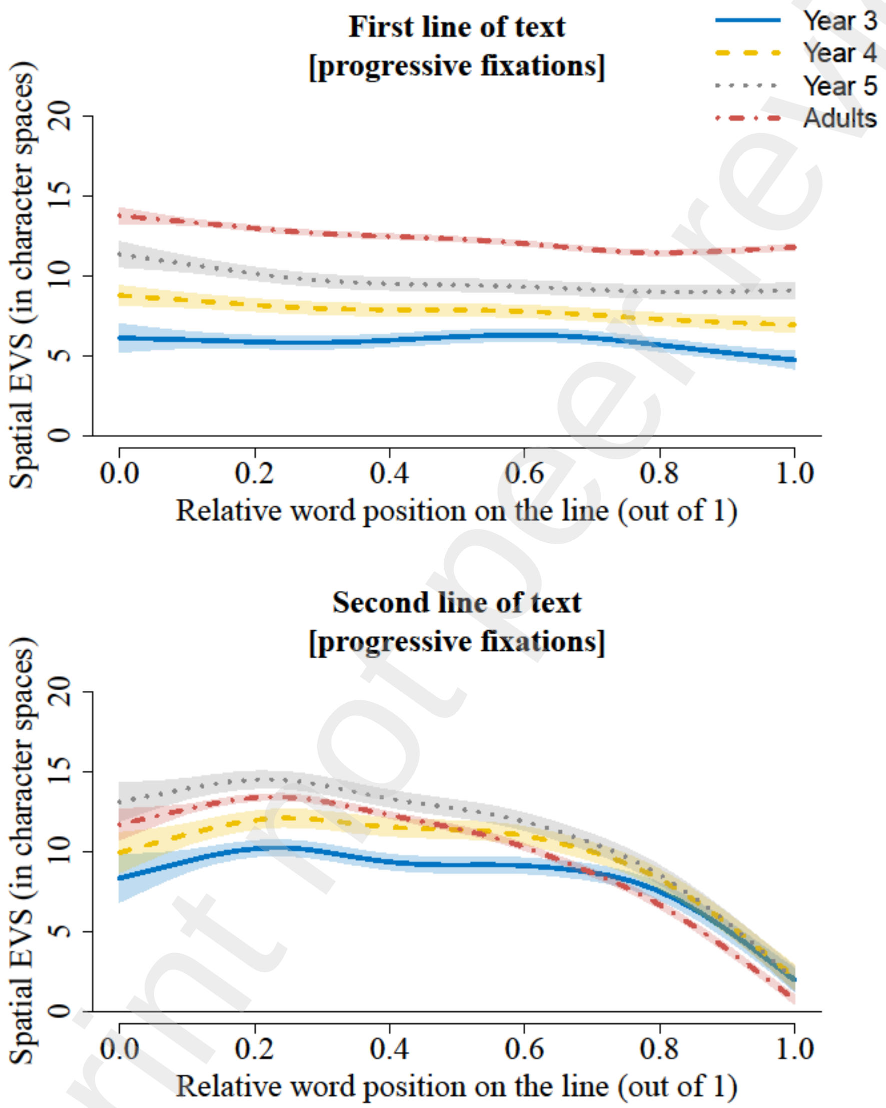
	Line 1				**Line 2**			
Predictors	*Estimate*	*std. Error*	*Statistic*	*p*	*Estimate*	*std. Error*	*Statistic*	*p*
(Intercept)	9.550	0.079	120.663	**<0.001**	9.813	0.102	96.590	**<0.001**
Year 4 vs. 3	1.900	0.138	13.743	**<0.001**	1.614	0.153	10.574	**<0.001**
Year 5 vs. 4	1.785	0.105	17.064	**<0.001**	1.431	0.121	11.838	**<0.001**
Adults vs Year 5	2.724	0.182	14.974	**<0.001**	-1.353	0.248	-5.454	**<0.001**
s(subject)			0.000	0.536			0.000	**<0.001**
s(item)			0.000	**<0.001**			0.000	**<0.001**
s(RWP)			10.178	**<0.001**			169.514	**<0.001**
s(RWP) × Year 3			3.998	**0.004**			29.083	**<0.001**
s(RWP) × Year 4			0.450	0.509			21.469	**<0.001**
s(RWP) × Year 5			3.187	**0.035**			0.005	0.987
s(RWP) × Adults			3.785	**0.002**			3.573	**0.003**
s(RWP, subject)			493.154	**<0.001**			244.571	**<0.001**
s(RWP, item)			78.162	**<0.001**			29.668	**<0.001**
Observations	42226				24982			
R^2	0.064				0.348			

For the first line, the fixed-effect results showed that, the EVS of children in Year 3 was significantly smaller from that of children in Year 4 (*d* = 0.32). The same pattern was found for the comparisons between Year 4 vs 5 (*d* = 0.31), and between Year 5 vs Adults (*d* = 0.57), with more experienced readers showing larger EVSs. The smooth term of RWP was significant (*edf* = 4.10), showing a non-linear general tendency for the EVS to decrease with greater word position on the line (see Figure 2). This pattern was a bit clearer when examining the interaction smooth term between RWP and each participant group. This represents the extent to which the EVS was modulated by word position within each group, and it was significant for all groups (ps < .05), except children in Year 4. Children in Year 4 showed a non-significant linear decrease in the EVS within the line (*edf* = 1.01), whereas Year 3 children (*edf* = 3.03), Year 5 children (*edf* = 1.67), and Adults (*edf* = 4.34), showed a similar, but more non-linear effect. Overall, all groups showed a decrease of the EVS at the end of the first line.

For the second line, the fixed-effect results showed that, the EVS of children in Year 3 was significantly smaller from that of children in Year 4 (*d* = 0.49). The same pattern was found for the comparisons between Year 4 vs 5 (*d* = 0.30), with more experienced readers showing larger EVSs. However, the Year 5 vs Adult comparison indicated the opposite pattern (*d* = - 0.26), with adults exhibiting a smaller EVS. The smooth term of RWP was also significant (*edf* = 7.38), showing the same non-linear tendency for the EVS to decrease towards the end of the line. This trend was stronger than the one observed on Line 1, mostly because there was no more text to read after Line 2 and the eyes and voice converged on the same location at the end of the trial. The interaction smooth terms of RWP and Participant Group were also significant for all groups except Year 5 (ps < .05). Children in Year 3 (*edf* = 3.48), Year 4 (*edf* = 2.31) and Adults (*edf* = 4.03) all showed a non-linear decrease towards the end of the line. Although children in Year 5 (*edf* = 3.39) also showed a similar pattern, this effect was not significant. Overall, there was a decline in EVS toward the end of the second line for all groups. In summary, most readers showed a non-linear modulation of the EVS within the line, with an overall decrease at the end of the first line. This reduction in EVS was stronger on the second line as participants reached the end of the text and group differences in the EVS began to disappear.

Figure 2

Modulation of EVS at Articulation Onset by Relative Word Position for Lines 1 and 2. Word position was calculated as a proportion out of all words on the line. Shading indicates ± 2 SE



3.3. How Does the EVS Change at Line Boundaries?

While the GAMM results above show how the EVS changes as readers progress through the line of text, they do not tell us exactly what occurs at line breaks when readers need to make a return-sweep to the following line. To answer our second research question, we examined how the EVS changes when the return-sweep saccade is executed. To do so effectively, it is necessary to investigate the EVS at the start of fixations (rather than at the start of articulation, as was done in Section 3.2), giving us a more refined measure of its dynamics. We therefore examined the EVS at three types of fixations which are adjacent to the return-sweep saccade, i.e., line-final, accurate line-initial, and undersweep fixations, and compared these to intra-line fixations which are not adjacent to return-sweeps.

The LMM results are presented in Table 5 and descriptive statistics are shown in Table 3. The EVS was significantly shorter at the onset of line-final compared to intra-line fixations (a difference of 0.4-character spaces (*d* = 0.08). Additionally, the EVS was significantly *longer* at the onset of undersweep fixations compared to intra-line fixations, a difference of 3-character spaces (*d* = 0.64). However, there was no difference between accurate line-initial and intra-line fixations and no interactions with Participant Group. These results indicate that the EVS is reduced slightly at the final fixation on the line, remains stable at the start of accurate line-initial fixations, and increases substantially during undersweep fixations. The same pattern was observed for all participant groups.

Table 5

LMM Results showing EVS at Fixation Onset as a function of Fixation Type and Participant Group

Predictors	*Estimate*	*std. Error*	*Statistic*	*p*
(Intercept)	13.723	0.264	51.966	**<0.001**
Intra-line vs Line-final	-0.380	0.120	-3.158	**0.002**
Intra-line vs Accurate	0.022	0.169	0.129	0.898
Intra-line vs Undersweep	3.132	0.134	23.301	**<0.001**
Year 4 vs 3	0.524	0.787	0.666	0.505
Year 5 vs 4	2.601	0.728	3.574	**<0.001**
Adults vs Year 5	-0.969	0.623	-1.556	0.120
Intra-line vs Line-final ×Year 4 vs 3	-0.202	0.400	-0.504	0.614
Intra-line vs Accurate × Year 4 vs 3	-0.538	0.574	-0.938	0.349

Intra-line vs Undersweep × Year 4 vs 3	0.112	0.431	0.261	0.794
Intra-line vs Line-final × Year 5 vs 4	-0.473	0.349	-1.355	0.176
Intra-line vs Accurate × Year 5 vs 4	0.432	0.488	0.885	0.376
Intra-line vs Undersweep × Year 5 vs 4	-0.590	0.391	-1.511	0.131
Intra-line vs Line-final × Adults vs Year 5	0.211	0.269	0.783	0.434
Intra-line vs Accurate × Adults vs Year 5	0.514	0.355	1.448	0.147
Intra-line vs Undersweep × Adults vs Year 5	-0.338	0.322	-1.050	0.294
Random Effects				
σ^2	23.691			
$\tau_{00\ \text{subject}}$	4.900			
$\tau_{00\ \text{item}}$	0.570			
ICC	0.188			
N_{subject}	103			
N_{item}	84			
Observations	57796			
Marginal R^2 / Conditional R^2	0.037 / 0.218			

3.4. How are Fixation Durations Before and After the Return-sweep Saccade Modulated by the EVS?

Following up on the previous analysis, our third research question examined whether fixation durations are modulated by the EVS at fixation onset, and whether these effects are more pronounced along line boundaries. The LMM results are presented in Table 6 and illustrated in Figures 3 and 4. We included additional covariates in keeping with Laubrock and Kliegl (2015), such as incoming and outgoing saccade direction and size, number of fixations per word, fixation position within the word, and previous word characteristics, including length and frequency.

There was a significant main effect of EVS, which was due to fixation durations increasing with greater EVS at fixation onset. The effect of Participant Group also demonstrated the expected pattern of results: fixation durations were shorter in Year 4 vs Year 3 (*d* = 0.15), in Year 5 vs

Year 4 (*d* = 0.21), and in Adults vs Year 5 (*d* = 0.44). In other words, fixation durations decreased in groups with greater age and reading experience. All Group contrasts were significant, except for the difference between Year 4 and Year 3, which was a bit weaker.

The effect of Fixation Type was also significant for all contrasts. Relative to intra-line fixations, line-final fixations increased by 47 ms (*d* = 0.37), accurate line-initial fixations increased by 179 ms (*d* = 1.19), whereas undersweep fixations *decreased* by a 90 ms (*d* = -0.93). This pattern of results mostly mirrors previous research, except that line-final fixations have previously been shown to be slightly shorter than intra-line fixations for both children and adults during silent reading (e.g. Parker et al., 2019), which was not observed here. Rather, line-final fixations increased relative to intra-line fixations.

There were significant interactions between EVS and the contrasts between intra-line and line-final and intra-line and accurate line-initial fixations. While a larger EVS led to increased fixation durations for intra-line fixations, this effect was significantly stronger for line-final fixations. This amplified effect at line-final fixations suggests that, when the EVS is large, readers pause for longer before a return-sweep saccade compared to before intra-line saccades. On the other hand, accurate line-initial fixations exhibited a mostly negative slope (except in Year 4), meaning that they were terminated sooner when the EVS was larger. There was no significant interaction between EVS and the contrast between undersweep and intra-line fixations; however, the three-way interaction with Participant Group (Adults vs Year 5) was significant. As Figure 3 shows, for adults, undersweep fixations were not modulated by the EVS, whereas intra-line fixations showed the usual positive relationship. For Year 5 children, largely the opposite was true: undersweep fixations showed positive modulation by EVS, whereas intra-line fixations showed weak to no effect of EVS.

There were also a few interactions between Participant Group and Fixation Type (see Figure 4). The difference in fixation durations between intra-line and line-final fixation durations significantly reduced in Year 5 children compared to Year 4 children and in Adults compared to Year 5 children. Likewise, the difference between intra-line and accurate line-initial fixation durations decreased significantly from Year 5 to the Adults. Finally, the difference between intra-line and undersweep fixation durations also significantly decreased from Year 4 to Year 5. Therefore, the difference between fixation durations that are adjacent to return-sweeps and those that are not were more pronounced in Years 3 and 4. Some of these effects then tended to become smaller in Year 5 children and Adults.

Table 6

LMM Results showing Log-transformed Fixation Durations as a Function of the EVS and Fixation Type (excluding ixations)

Predictors	*Estimate*	*std. Error*	*Statistic*	*p*
(Intercept)	2.398	0.010	243.791	**<0.001**
EVS at Fixation Onset	0.009	0.002	6.151	**<0.001**
Intra-line vs Line-final	0.063	0.008	8.033	**<0.001**
Intra-line vs Accurate	0.216	0.010	21.710	**<0.001**
Intra-line vs Undersweep	-0.167	0.011	-15.780	**<0.001**
Year 4 vs 3	-0.029	0.019	-1.525	0.127
Year 5 vs 4	-0.042	0.018	-2.384	**0.017**
Adults vs Year 5	-0.058	0.015	-3.834	**<0.001**
Word Frequency	-0.012	0.001	-7.879	**<0.001**
Word Length	0.021	0.002	9.670	**<0.001**
Previous Word Length	-0.005	0.002	-3.367	**0.001**
Previous Word Frequency	-0.012	0.002	-7.585	**<0.001**
Outgoing Saccade direction[Backw. vs Forw.]	0.076	0.003	23.548	**<0.001**
Incoming Saccade direction[Backw. vs Forw.]	0.022	0.007	2.949	**0.003**
Outgoing Saccade Size	-0.020	0.003	-6.550	**<0.001**
Incoming Saccade Size	0.050	0.003	16.303	**<0.001**

Number of Fixations	-0.003	0.001	-2.215	**0.027**
Fixation Sequence Number	-0.012	0.001	-8.501	**<0.001**
EVS × Intra-line vs Line-final	0.055	0.007	7.969	**<0.001**
EVS × Intra-line vs Accurate	-0.025	0.010	-2.632	**0.008**
EVS × Intra-line vs Undersweep	0.001	0.007	0.127	0.899
EVS ×Year 4 vs 3	-0.001	0.005	-0.231	0.817
EVS × Year 5 vs 4	-0.007	0.004	-1.717	0.086
EVS × Adults vs Year 5	0.001	0.003	0.363	0.717

Table 6 continued

Predictors	*Estimate*	*std. Error*	*Statistic*	*p*
Intra-line vs Line-final ×Year 4 vs 3	-0.007	0.019	-0.392	0.695
Intra-line vs Accurate × Year 4 vs 3	-0.012	0.029	-0.425	0.671
Intra-line vs Undersweep × Year 4 vs 3	0.029	0.025	1.158	0.247
Intra-line vs Line-final × Year 5 vs 4	-0.062	0.017	-3.759	**<0.001**
Intra-line vs Accurate × Year 5 vs 4	-0.005	0.024	-0.226	0.821
Intra-line vs Undersweep × Year 5 vs 4	0.091	0.025	3.655	**<0.001**
Intra-line vs Line-final × Adults vs Year 5	-0.053	0.013	-4.050	**<0.001**
Intra-line vs Accurate × Adults vs Year 5	-0.052	0.018	-2.800	**0.005**
Intra-line vs Undersweep × Adults vs Year 5	0.021	0.021	1.005	0.315
Word Frequency × Word Length	-0.009	0.002	-6.145	**<0.001**
EVS × Intra-line vs Line-final × Year 4 vs 3	0.025	0.022	1.138	0.255
EVS × Intra-line vs Accurate × Year 4 vs 3	0.023	0.034	0.665	0.506
EVS × Intra-line vs Undersweep × Year 4 vs 3	-0.004	0.023	-0.189	0.850
EVS × Intra-line vs Line-final × Year 5 vs 4	-0.024	0.021	-1.156	0.248
EVS × Intra-line vs Accurate × Year 5 vs 4	-0.007	0.025	-0.290	0.772
EVS ×Intra-line vs Undersweep × Year 5 vs 4	0.027	0.020	1.324	0.186

EVS ×Intra-line vs Line-final × Adults vs Year 5	0.017	0.017	0.996	0.319
EVS × Intra-line vs Accurate × Adults vs Year 5	-0.012	0.016	-0.759	0.448
EVS × Intra-line vs Undersweep × Adults vs Year 5	-0.034	0.017	-2.078	**0.038**
Random Effects				
σ^2	0.032			
$\tau_{00\ \text{subject}}$	0.003			
$\tau_{00\ \text{item}}$	0.000			
ICC	0.083			
N_{subject}	103			
N_{item}	84			
Observations	41152			
Marginal R^2 / Conditional R^2	0.135 / 0.207			

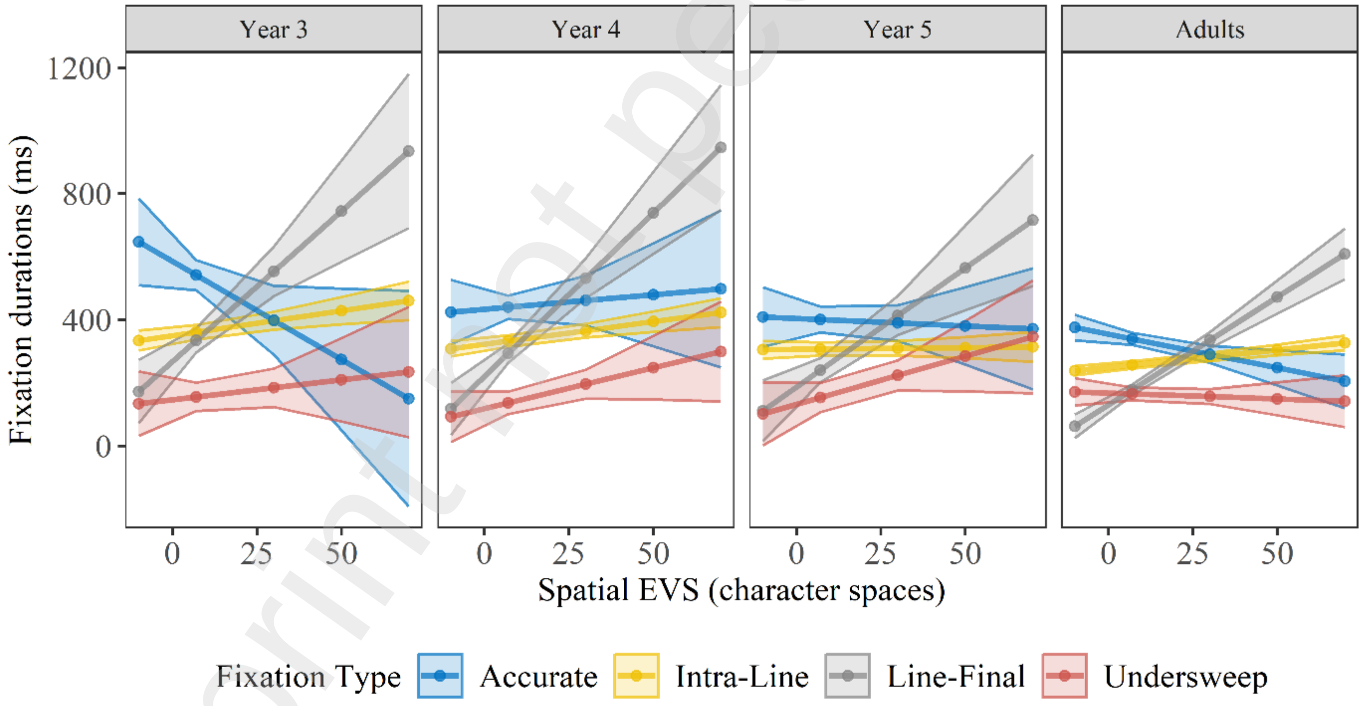


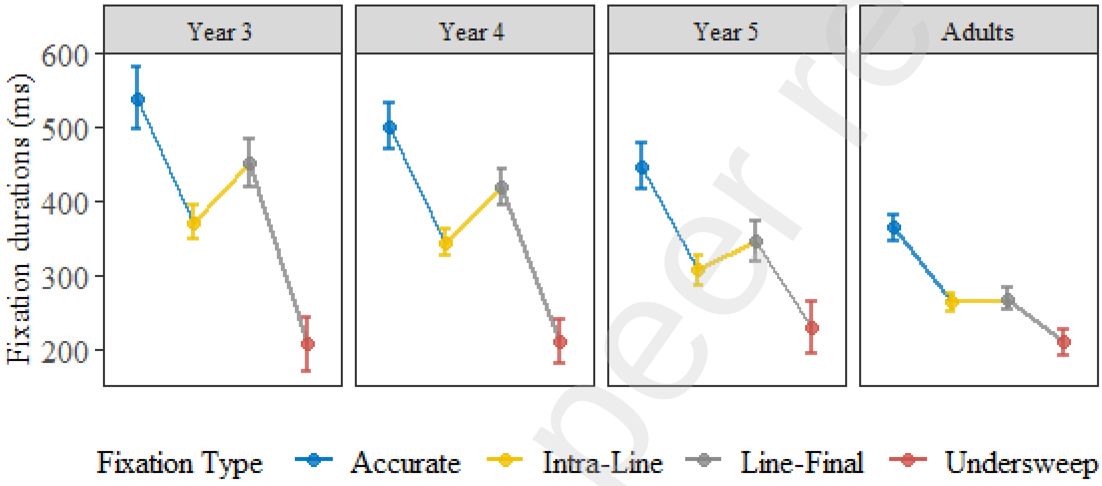
Figure 3

Line Effect Plots Showing the Interaction between EVS at Fixation Onset, Fixation Type and Participant Group for Untransformed Fixation Durations.

Note. A larger EVS indicates a greater eye-to-voice distance, while smaller values indicate shorter distances. EVS. Shading represents ± 2 SE. The fitted values were extracted from the model using the effects package v 4.2-2 (Fox & Weisberg, 2019).

Figure 4

Line Effect Plots Showing the Interaction between Fixation Type and Participant Group for Untransformed Fixation Durations.



Note. Error bars shows represents ± 2 SE. The fitted values were extracted from the model using the effects package v 4.2-2 (Fox & Weisberg, 2019)

3.5 How Does the EVS Influence Articulation Rates?

Finally, our last research question examined whether articulation rates play a role in EVS dynamics. If articulation rates are influenced by the EVS, this would suggest that eye-movements are not the sole determinant of the EVS, but that readers can also adjust their articulation rate to maintain a comfortable span. In this analysis, we predicted the articulation rate for each word (in phonemes per second) from the EVS at the start of word articulation and the Participant Group. The LMM results are presented in Table 7 and visualised in Figure 5.

There was a main effect of the EVS on articulation rate, indicating that a one-character-space increase in spatial EVS corresponded to an additional one-phoneme-per-second increase in articulation rate. In other words, a larger EVS was associated with higher articulation rates, meaning that readers speed up their articulation when the EVS is large. Articulation rates showed similar group differences to fixation durations: articulation rates did not differ between Year 3 and 4 (*d* = -0.04), but they were significantly faster in Year 5 compared to Year 4 (*d* = 0.36) and also in Adults compared to Year 5 ((*d* = 0.98; see Table 2). Additionally, there was a significant interaction between EVS and the comparison between Adults and Year 5 children, and the comparison between Year 5 and 4, whereby the EVS effect was significantly smaller for Adults compared to Year 5 children, and for Year 5 children compared to Year 4 children (see Figure 5). Overall, these results indicate that articulation rates can indeed change based on how large the EVS is. Additionally, more skilled readers seem to rely less on changes in articulation to maintain a comfortable span, though such modulation still exists even in those groups.

Table 7

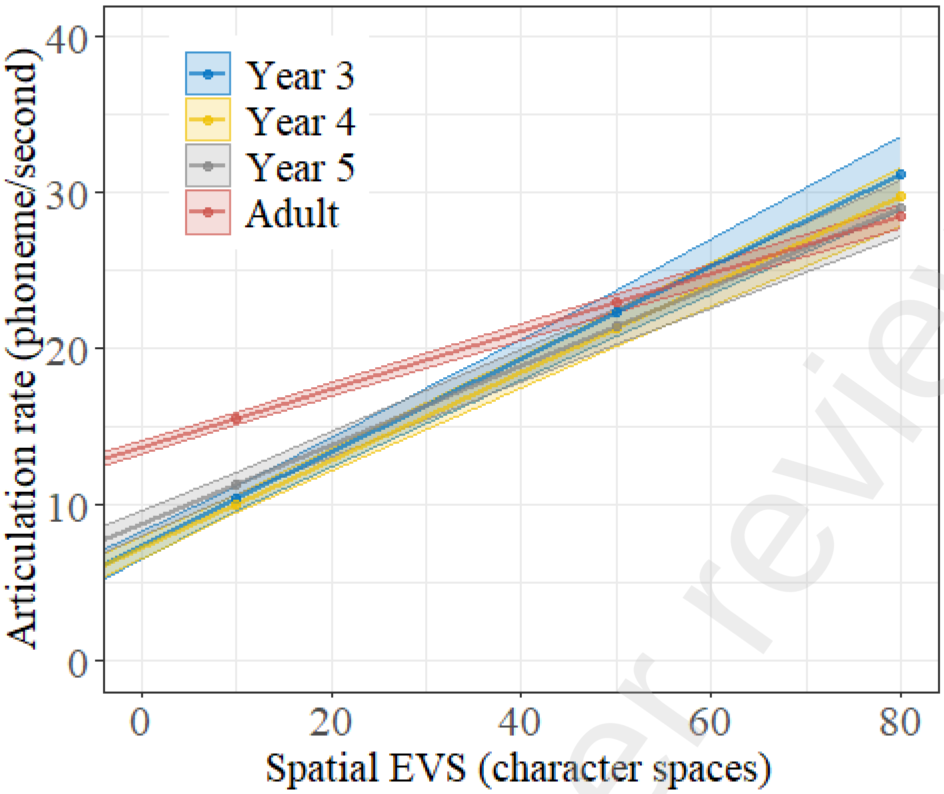
LMM Results showing Log-transformed Articulation Rates as a Function of the EVS at Articulation Onset and Participant Group

Predictors	*Estimate*	*std. Error*	*Statistic*	*p*
(Intercept)	1.026	0.006	173.916	**<0.001**
EVS at Articulation Onset	0.101	0.004	26.281	**<0.001**
Year 4 vs 3	-0.005	0.017	-0.317	0.751
Year 5 vs 4	0.055	0.016	3.445	**0.001**
Adults vs Year 5	0.148	0.014	10.744	**<0.001**
Word Frequency	0.043	0.001	63.035	**<0.001**
Previous Word Frequency	-0.009	0.001	-7.689	**<0.001**
Previous Word Length	-0.007	0.001	-5.919	**<0.001**

EVS × Year 4 vs 3	-0.004	0.012	-0.339	0.735
EVS × Year 5 vs 4	-0.028	0.011	-2.471	**0.013**
EVS × Adults vs Year 5	-0.045	0.009	-4.835	**<0.001**
Random Effects				
σ^2	0.020			
$\tau_{00\ \text{subject}}$	0.002			
$\tau_{00\ \text{item}}$	0.000			
$T_{11\ \text{subject (spatial EVS)}}$	0.001			
$\rho_{01\ \text{subject}}$	-0.475			
ICC	0.119			
N_{subject}	103			
N_{item}	84			
Observations	47718			
Marginal R^2 / Conditional R^2	0.346 / 0.424			

Figure 5

Line Effect Plots Showing the Interaction between EVS at Articulation Onset and Participant Group for Untransformed Articulation Rates



Note. Shading represents ± 2 SE. The fitted values were extracted from the model using the effects package v 4.2-2 (Fox & Weisberg, 2019).

4.0. Discussion

The present study explored how the EVS changes both within and between lines, using an eye-movement corpus of children reading aloud and comparing them to adults reading the same passages. We examined whether the EVS changes based on the relative word position on the line, and also before and after readers make a return-sweep to a new line. We further explored the relationship between EVS and articulation rates to probe the complex dependency between eye-movements and articulation rates that allows readers to maintain a comfortable span.

The results mostly showed a non-linear modulation of the EVS by relative word position with a decrease towards the end of the line, which was more pronounced for the second line. Although this effect was small, this result was somewhat corroborated by the observation of shorter EVS at the onset of line-final fixations compared to intra-line fixations, suggesting that the eyes are more likely to wait for the voice to catch up at line breaks. However, the EVS at the start of undersweep fixations was longer, relative to intra-line fixations. Additionally, consistent with previous studies in adults (Laubrock & Kliegl, 2015), the EVS affected intra-line fixation durations in children as well as adults. The data showed, for the first time, that the EVS consistently impacted line-final fixations more strongly than other fixation types across all participant groups. Additionally, the EVS impacted articulation rates, meaning that readers sped up their articulation when the EVS was large. We discuss these key findings, along with additional results, below.

4.1. EVS Within and Between Lines

The position of a word within a text has been shown to influence eye movement metrics (Kuperman et al. 2010), although its effect on the EVS has been less well established. Using two measures and methods adopted by Buswell (1920) and Fairbanks (1937), we found similar patterns regarding EVS changes within and between lines. When the EVS was measured at the onset of each word's articulation (Buswell, 1920), the span showed a non-linear pattern for most groups with an overall tendency to decrease towards the end of the line. This pattern indicates that, as readers begin to articulate the final words on a line, their eyes either slow relative to the start of the line and/or their voice speeds up. Typically, at the start of articulation of the line-final word, readers' eyes are already on the next line. Therefore the shortened span could be due to a delay in the eyes' forward movement after the return-sweep e.g., saccade programming resulting in longer accurate line-initial fixations (Parker et al. 2025) or due to corrective saccades. It could also be due to speeding up of the voice as readers accumulate more context across the line. Although no studies demonstrate that reading rate accelerates across extended texts, research shows that articulation rates increase as a conversation progresses (Schulman, 2010).

Similarly, using a fixation type approach based on Parker et al. (2019) and EVS measure adopted by Fairbanks (1937) measured at the onset of fixation, our results show that the EVS is significantly smaller for line-final fixations compared to intra-line fixations, somewhat corroborating the finding of a decrease in EVS towards the end of lines. Additionally, the EVS at the start of undersweep fixations was larger compared to intra-line fixations for all groups of readers which aligns with previous research showing that larger EVS at the beginning of lines arise from return-sweep inaccuracies (Fairbanks, 1937), which are followed by a leftward corrective saccade because these saccades typically land farther from the left margin than accurate line-initial fixations. In sum, these patterns replicate earlier findings and extend them by demonstrating a mostly non-linear modulation of the EVS within lines with a more pronounced decrease in EVS as readers reach the end of a text.

4.2. Modulation of Fixation Durations by the EVS Within and Between Lines

This research confirms previous work in skilled readers by replicating similar EVS effects on fixation durations in children (Inhoff et al., 2011; Laubrock & Kliegl, 2015). A larger EVS was associated with longer fixation durations. We extend this evidence by showing, for the first time, that this relationship is stronger for line-final fixations in both children and adults. Previous work (Hofmeister, 1997; Kuperman et al., 2010; Parker, Slattery, et al., 2019) suggest a parsimonious explanation for the termination of line-final fixations: these fixations support the planning of return-sweep saccades and may be less involved in linguistic processing. In line with our predictions, the stronger relationship between EVS and line-final fixations may reflect a process-monitoring mechanism that ensures a manageable EVS before the execution of a costly return-sweep (Adedeji et al., 2021; Levasseur et al., 2006). Essentially, even with an overall reduced EVS for line-final fixations, readers may still need to ensure that the voice catches up with the eyes before making return-sweep movements. We suggest that if the span is not sufficiently reduced before the return sweep, readers may be at risk of making regressions to the previous line (Laubrock & Kliegl, 2015). These findings extend current accounts of line-final fixation mechanisms, which are typically considered to be driven by oculomotor processes and less so by lexical processes (Parker et al., 2025). However, during oral reading, cognitive processes appear to play a more prominent role for line-final fixations.

Adedeji et al. (2021) found a significant oral-reading cost, with longer fixation durations during oral compared to silent reading for accurate line-initial fixations relative to intra-line fixations. Therefore, we expected that fixation durations would be more strongly driven by larger EVSs for accurate line-initial fixations than for intra-line fixations. However, this was not the case; the EVS impacted accurate line-initial fixations to a lesser extent compared to intra-line fixations. In fact, the result showed that larger spans were followed by shorter fixation durations. While the reasons for these are not currently clear, these results indicate that longer fixation durations and EVS control are independent mechanisms during oral reading.

Surprisingly, the effect of the EVS on undersweep fixations did not differ substantially from its effect on intra-line fixations. This pattern was evidenced by a non-significant interaction between EVS and undersweep fixations relative to intra-line fixations, alongside a group difference in the EVS-undersweep interaction for Year 5 children compared with adults. The plots in Figure 3 show that the EVS effect on undersweep fixations is effectively absent in adults. This effect in children was unexpected because undersweep fixations are typically assumed to be terminated primarily by oculomotor error-correction mechanisms, rather than by higher-level cognitive or linguistic factors (Becker, 1972; Becker & Fuchs, 1969; Hofmeister, 1997). It is therefore puzzling that the EVS exerted a similar influence on undersweep fixations as on intra-line fixations. To investigate this pattern further, we modelled the interaction between EVS and the landing positions of undersweep fixations (see Table S3). Existing research shows that the time required to correct an undershoot error decreases as the undershoot lands farther from the intended target (Becker, 1972; Becker, 1989; Fischer et al., 1993; Ohl et al., 2011). 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 appeared inhibited. A larger EVS accompanied by a more distant landing position from the left margin led to longer undersweep fixation durations. This inhibition may work similar to the time-delayed foveal inhibition mechanism assumed in the SWIFT model where the autonomous timer which generates saccades is only inhibited when current foveal difficulty is high (Laubrock et al., 2006). In order words, the automatic corrective saccade process may be suppressed by a top down cognitive process.

The EVS appeared to have an effect on most fixation types, although its magnitude depended on the participant group. However, the most robust finding across all groups was the strong positive effect of the EVS on line-final fixations. This pattern suggests that coordination between perception and production during oral reading is driven primarily by general cognitive processes such as working memory (Kubler et al., 2022) rather than by linguistic or purely oculomotor processes. Buswell (1920) proposed that the EVS and linguistic skills are both driven by attentional and memory processes, rather than one being the cause of the other. Thus, although the EVS relates to linguistic skills, it also reflects high-order working memory which influences even basic oculomotor behaviours, such as the termination of undersweep fixations or return-sweep planning. This interpretation aligns with cognitive-control accounts of corrective saccade initiation (Ray et al., 2004) and with evidence that working memory shapes eye movement behaviour (Loh et al., 2022; Luke et al., 2018). Additionally, this coordinative mechanism may be particularly evident for fixation types that engage more oculomotor planning and correction (i.e., line-final and undersweep fixations). Further research is certainly required to determine how generalisable these findings.

4.3. Fixation Durations around Line Boundaries During Oral Reading

Other findings from this study further elucidate the mechanisms underlying oral reading. While speed-up effects have been documented during silent reading (Abrams & Zuber, 1972;

Hofmeister, 1998; Parker, Nikolova, et al., 2019; Parker, Slattery, et al., 2019), the current study reveals a slow-down at the end of the line during oral reading, which was particularly strong in children. This pattern is consistent with Adedeji et al. (2021) who found a marginally greater oral reading cost for line-final fixations compared to intra-line fixations in adults, suggesting that readers may slow down more before the return-sweep saccade was executed during oral reading. As Figure 4 shows, the increase in line-final fixation durations relative to intra-line fixations declines with reading experience, with adults showing similar durations for intra-line and line-final fixation types. This pattern, although directionally reversed, resembles the developmental trajectory of speed-up effects during silent reading. German Grade two children show no line-final speed-up effects in gaze duration, compared Grade three children and adults (Tiffin-Richards & Schroeder, 2018). While speed-up effects increase with development during silent reading, the magnitude of slowdown decreases with development during oral reading. Thus, explanations for speed-up effects based on return-sweep planning efficiency (Kuperman et al., 2010) or parafoveal processing capacity (Rayner, 1977) may be disrupted during oral reading. However, this disruption may be functional, facilitating more fluent oral reading by supporting eye–voice coordination at line boundaries, especially for children.

Accurate line-initial fixations also appear to be impacted by the demands of oral reading. In children's silent reading, accurate line-initial fixation durations do not differ significantly from intra-line fixation durations (Parker, Slattery, et al., 2019), indicating that children rely on foveal processing at the start of the line and within lines in the same way. In contrast, adults exhibit longer accurate line-initial fixations during silent reading due to a lack of preview at the start of the line and subsequent parafoveal preview within the line (Parker, Slattery, et al., 2019). Furthermore, these durations increase substantially during oral reading (Adedeji et al., 2021). Consistent with this pattern, the present study found that accurate line-initial fixations were significantly longer than intra-line fixations for both children and adults during oral reading. Children's longer accurate line-initial fixations relative to intra-line fixations during oral reading may suggest that readers allocate extra time at line starts for planning and eye–voice coordination, particularly given the added cognitive demands of oral reading alongside lexical and oculomotor processing (Parker et al., 2025).

4.4. The Role of Articulation During Eye-Voice Coordination

The final analysis of our study sought to provide evidence for the modulation of articulatory processes by the EVS. Indeed, we found that when the EVS was large at the onset of word articulation, articulation rates were higher than when the EVS was smaller, even after controlling for word frequency. These findings support Fairbanks (1937), indicating that both speech and oculomotor processes actively and jointly influence the width of the EVS. Furthermore, the interaction between groups and EVS shows that as reading skill develops, articulation or oral reading rates peak (Calabrese et al., 2016) and readers are less likely to use the articulatory mechanism to support EVS modulation.

4.5. Summary and Conclusion

In summary, the findings from this study extend previous evidence in adults to developing readers and provide new insights into how the EVS changes both with lines and between line during oral reading. Critically, several patterns held similar between children and adults, such as similar non-linear modulation of the EVS within lines, fixation type effect on the EVS, and EVS effects on fixation durations for line-final fixations and articulation rates. Although further research is needed to clarify how the EVS modulates undersweep fixations in children, the strong effect of the EVS on line-final fixations in both children and adults suggests that line boundaries serve a functional role in supporting fluency. This may be especially true for children, who read aloud more often and are more affected by disruptions in the flow of oral reading. Theoretically, this pattern points to high-level cognitive influence beyond linguistic or oculomotor factors, which was more pronounced at line boundaries, likely due to the costly nature of return-sweeps or the temporary break in information uptake. Finally, the increase in articulation rates when the EVS is large suggests that these high-level cognitive influences extend to post-lexical speech production processes.

To conclude, the present results show that the EVS is modulated at line boundaries, particularly for children who primarily read aloud. More research is needed to understand how eye-voice coordination processes contribute to overall reading performance and fluency. Clarifying how eye-voice coordination changes with development and reading skill presents a promising direction for future research.

Declarations

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Declarations of interest

The authors declare that they have no conflict of interest.

Availability of data and code

The datasets generated and analysed during the current study are available in the Open Science Framework (OSF) repository, https://osf.io/t3h2p/?view_only=1057c556d70747458041e2e669278a40

Authors Contribution's

Conceptualization: VIA, JAK, TJS; **Methodology:** VIA, TJS, MRV; **Formal analysis and investigation:** VIA, TJS, MRV; **Writing:** VIA, MRV, JAK, TJS.

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Eye-Voice Coordination during Children and Adult's Multiline Reading

Victoria I. Adedeji[1][2],

Timothy J. Slattery[2],

Julie A. Kirkby[2]

and

Martin R. Vasilev[3]

[1] School of Psychology and Vision Sciences, University of Leicester, United Kingdom

[2]Department of Psychology, Bournemouth University, United Kingdom

[3]Department of Experimental Psychology, University College London, United Kingdom

Victoria I. Adedeji https://orcid.org/0000-0001-8031-0815
Timothy J. Slattery https://orcid.org/0000-0002-2652-289X
Julie, A. Kirkby https://orcid.org/0000-0001-6502-0676
Martin R. Vasilev https://orcid.org/0000-0003-1944-8828

Correspondence regarding this article should be addressed to Victoria I. Adedeji, School of Psychology and Vision Sciences, University of Leicester, LE1 7RH United Kingdom; Email: via4@leicester.ac.uk