Undersweep-fixations during reading in adults and children.

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Abstract

Return-sweeps take a reader's fixation from the end of one line to the start of the next. Return-sweeps frequently undershoot their target and are followed by a corrective saccade towards the left margin. The pauses prior to correctives saccades are typically considered to be uninvolved in linguistic processing. However, recent findings indicate that these undersweep-fixations influence skilled adult reader's subsequent reading pass across the line and provide preview of line-initial words. This research examined these effects in children. First, a children's reading corpus analysis revealed that words receiving an undersweep-fixation were more likely skipped and received shorter gaze durations during a subsequent pass. Second, a novel eye movement experiment which directly compared adults' and children's eye movements indicated that, during an undersweep-fixation, readers very briefly allocate their attention to the fixated word—as indicated by inhibition of return effects during a subsequent pass—prior to deploying attention towards the line-initial word. We argue that, prior to the redeployment of attention, readers extract information at the point of fixation that facilitates later encoding and saccade targeting. Given similar patterns of results for adults and children, we conclude that the mechanisms controlling for oculomotor coordination and attention necessary for reading across line boundaries are established from a very early point in reading development.

Keywords: Eye movements, reading, return-sweeps, undersweep-fixations, oculomotor control, attention

Adults and children perform saccadic eye movements during reading in order to fixate words in high-acuity foveal vision. Saccades are separated by pauses, called fixations, during which readers encode information from the text (Rayner, 1998). For English readers, the majority of saccades occur from left-to-right. Yet, right-to-left movements are observed. One particular right-to-left movement is the return-sweep. Return-sweeps take a reader's point of fixation from the end of one line to the beginning of the next. Like all saccades, return-sweeps are prone to error (McConkie, Kerr, Reddix, & Zola, 1988). Both adults and children frequently undershoot line-initial words and require corrective leftwards saccades to fixate their intended target (Parker, Slattery, & Kirkby, 2019). The intervening fixations between return-sweeps and corrective saccades have been termed "undersweep-fixations" (Parker, Kirkby, & Slattery, 2017). A tacit assumption is that undersweep-fixations are the result of oculomotor error and reflect little to no influence on ongoing linguistic processing. Yet recent studies have shown that skilled adult readers can acquire useful information about the word at the location of the undersweep-fixation (Slattery & Parker, 2019) and the word to the left of fixation (i.e. line-initial words; Parker & Slattery, 2019). We henceforth refer to this acquisition of information as the "undersweep preprocessing benefit". While skilled adult readers are able to acquire this information, it is currently unclear whether children are able to do this is in a similar manner. This is the focus of the current research.

Eye movements during reading in adults and children

Children read at a slower rate than adults. Children fixate words more frequently, their fixations are longer (Blythe & Joseph, 2011), and they refixate words at a higher rate (Joseph, Liversedge, Blythe, White, & Rayner, 2009). In addition, children's refixation saccades tend to be smaller than adults' and more often regressive in nature (Joseph et al., 2009). Like adults', children's eye movements appear sensitive to the lexical properties of the fixated word. Children are sensitive to both word length information (Blythe, Häikiö, Bertram, Liversedge, & Hyönä, 2011; Joseph et al., 2009) and lexical-frequency (Blythe, Liversedge, Joseph, White, & Rayner, 2009; Joseph, Nation, & Liversedge, 2013), with these effects being more pronounced in children demonstrating their increased sensitivity to lexical information.

Despite their increased sensitivity to lexical properties of the word, children appear similar to adults with regards to their oculomotor coordination and visual processing. For instance, both populations of readers target their saccades towards word centres (Joseph et al., 2009). Adults and children also appear similar in their rate of visual capture. Evidence from the disappearing text paradigm (Blythe et al., 2009, 2011) indicates that, within 60 ms, both adults and children are able to extract the necessary information for visual processing. This suggests that for even very short fixations, adults and children will be capable of processing information in those locations.

Like adults, children extract information from an asymmetrical window around their point of fixation (Rayner, 1986; Sperlich, Schad & Laubrock, 2015). However, developing readers have slightly smaller perceptual spans than adult readers (Häikiö, Bertram, Hyönä & Niemi, 2009; Rayner, 1986; Sperlich et al., 2015). Despite developmental differences in the perceptual span, evidence indicates that, like adults, children extract information from the parafoveal word (Pagán, Blythe, & Liversedge, 2015; Häikiö, Bertram & Hyönä, 2010; Marx, Hutzler, Schuster, & Hawelka, 2016; Tiffin-Richards & Schroeder, 2015). Thus, it would appear that, like adults, children are capable of deploying their attention beyond the current point of fixation.

Return-sweep saccades and undersweep-fixations

Parker et al. (2019) reported that adults and children require corrective saccades following 52% and 68% of return-sweeps respectively. For both participant groups, the likelihood of initiating a corrective saccade was influenced by line-initial landing position.

Line-initial fixations landing further from the left margin more frequently required corrective saccades. This finding is consistent with Becker (1976) who argued that the fixation preceding a corrective saccade is terminated based on the deviation of the saccade from its target which, if exceeding a tolerance threshold, triggers a corrective saccade. This account of correctives saccades assumes that information is sampled during the fixation that precedes the corrective saccade.

Fixations that intervene return-sweeps and corrective saccades have been termed "undersweep-fixations" (Parker et al., 2017). Undersweep-fixations are shorter than those typically observed during reading (128-156 ms) and appear uninfluenced by a word's lexical properties (Slattery & Parker, 2019). This is likely because many are terminated prior to the point at which lexical effects emerge over the fixation period (i.e. 110-150ms; Reingold & Sheridan, 2018). Thus, a significant portion of undersweep-fixations lie outside the window at which lexical effects emerge on fixation-duration.

The short duration of undersweep-fixations does not mean that information is not extracted and processed. Parker and Slattery (2019) reported that readers can acquire information to the left of undersweep-fixations as both single-fixation and gaze durations on line-initial words were shorter following an undersweep-fixation than when return-sweeps had accurately landed on the line-initial word. Second, Slattery and Parker (2019) reported that words receiving an undersweep-fixation were more likely to be skipped during a subsequent pass. If these words were fixated, the resulting gaze duration (not including the undersweep-fixation duration) was shorter than if it had not received an undersweep-fixation. Slattery and Parker hypothesised that, during a preattentive stage, readers acquire information, such as abstract letter identities, which are capable of surviving visual masking effects across fixations (McConkie & Zola 1979). Given that both adults and children are able to extract information necessary for linguistic processing within a 50-60 ms window

(Blythe et al., 2009, 2011), it is likely that children will be able to acquire information during an undersweep-fixation. However, differences in rates of lexical processing between adults and children may result in them differentially acquiring information from the fixated and/or adjacent word during an undersweep-fixation.

Of course, this would assume that readers are extracting information during an undersweep-fixation. Slattery and Parker (2019) reported that some of the undersweep-fixation effects may represent an oculomotor Inhibition of Return (IoR). IoR effects refer to the finding that it takes longer to redeploy attention to a previously attended location (see Klein, 2000 for a review). In these analyses, intra-line fixations preceding a return to a previously fixated word were longer than those that skipped a previously fixated word. These IoR effects were also present for fixations following an undersweep-fixation albeit to a lesser extent. By an IoR account, increased skipping following an undersweep-fixation may reflect an avoidance in redeploying attention to a previously fixated location. Regardless of interpretation, the influence of undersweep-fixations during subsequent reading in children remains unclear.

The current research

The current work had two aims. The first was to examine whether children evidence increased skipping rates and shorter gaze durations following an undersweep-fixation. The second was to examine whether the lexical properties of the fixated word modulate the extraction of information during these brief pauses in both adults and children. The examination of adults' and children's eye movements enabled a direct comparison of the processing afforded by undersweep-fixations at two distinct points in reading development. The first aim was examined via a linear mixed-effects analysis of data reported by Joseph, Bremner, Liversedge, and Nation (2015). The second aim was addressed in a novel eye movement experiment in which we manipulated the lexical-frequency of words occurring at the most likely location of an undersweep-fixation. We make specific predictions for each study below.

Given children's efficiency in visual processing (Blythe et al., 2009, 2011), it is expected that they would be able to extract information at the location of an undersweep-fixation. Assuming that, like adults, children extract information during an undersweep-fixation, skipping rates should be increased for words that previously received an undersweep-fixation. Similarly, the subsequent gaze durations on words that received an undersweep-fixation should be shorter than on words that did not receive an undersweep-fixation. These predictions paralleled the findings reported by Slattery and Parker (2019).

In our eye movement experiment, the lexical-frequency of the second word on a line was manipulated. This enabled us to test several predictions about the allocation of attention during an undersweep-fixation. Our predictions are derived from the theoretical extension of the E-Z Reader model outlined by Parker and Slattery (2019). Both E-Z Reader and our predictions are outlined below.

Because E-Z Reader has been described in detail elsewhere (e.g. Reichle & Sheridan, 2015), the following description is limited to the information necessary to understand the predictions we derive. E-Z Reader is classified as a serial attention shift model. It assumes that lexical processing moves the eyes through the text, with attention allocated to words in their printed order. As such, lexical processing of an upcoming word does not begin until the current word is processed. This contrasts models, such as SWIFT (Engbert, Nuthmann, Richter, & Kliegl, 2006), that allow for multiple words to be processed in parallel. E-Z Reader also assumes that the completion of an early stage of lexical processing (L1) provides the signal to being programming a saccade to the next word, whereas attention shifts when lexical access (L2) is complete for a word. As such, attention and eye movements are decoupled within E-Z Reader. Because the duration of L2 is usually shorter than the time required to program a saccade, attention usually moves to an upcoming word prior to the eye. Thus, readers can begin lexically processing word n+1 while fixating word n. If L1 completes for word n+1 in parafoveal vision, E-Z Reader will cancel the saccade to word n+1 and program a saccade to word n+2 instead. This decoupling allows E-Z Reader to explain mislocated fixations (Dreighe, Rayner, & Pollatsek, 2008). Mislocated fixations result from error in saccade execution (McConkie eta al., 1988) where under or overshoot results in a fixation on a word that is not the attentional target. When saccadic error is large enough, E-Z Reader implements a corrective saccade to bring the eye to an optimal position. While E-Z Reader assumes error in fixation behaviour, it assumes no error in the movement of attention.

The remaining E-Z Reader assumptions of importance to the current work are related to visual encoding, lexical processing, and saccadic programming and execution. While E-Z Reader assumes that information is propagated across the entire visual field, only a select amount of high-spatial frequency information about the attended word is used for lexical processing. Low-spatial frequency information in parafoveal and peripheral vision is used for saccade targeting. This information becomes available after a 50 ms eye-to-brain lag. E-Z Reader assumes that lexical processing is determined by a word's frequency and predictability in its surrounding sentence context. This allows it to explain why frequent and predictable words receive fewer, shorter fixations (Rayner, 1998). E-Z Reader assumes that the rate at which L1 completes is modulated by visual acuity, such that words close to the centre of vision receive fewer, shorter fixations (Rayner, 1998). With regards to saccade planning, E-Z Reader specifies two stages of saccade planning: an initial labile stage that can be cancelled by the initiation of another saccade program and a non-labile stage that cannot be cancelled or modified.

E-Z Reader has been successfully implemented to examine the concurrent development of eye movement control and reading skill (Mancheva et al., 2015; Reichle et al., 2013). Two general accounts exist to explain the differences in adults' and children's eye movements. The first posits that these differences reflect the fact that children are less skilled at moving their eyes. The alternative suggests that children are less proficient at identifying printed words and integrating their meanings into linguistic representations. To evaluate the plausibility of these two explanations, Reichle et al. conducted a series of simulations using E-Z Reader. The simulations were straightforward yet surprising. Only increasing the value of the parameter that controls the overall rate of lexical processing was sufficient to generate the findings related to children's first-pass eye movements. On the basis of these results, it was concluded that the primary reason for differences in adults and children are differences in their proficiency of lexical processing.

Based on E-Z Reader's current implementation, it is likely that the model's mechanism for corrective saccades would be capable of accounting for the existence of undersweep-fixations. With the additional assumption that no lexical processing of the first word on a new line can occur until the line-initial word is available in (para)foveal vision, E-Z Reader may be able to model return-sweep behaviour reasonably well. This would assume that return-sweeps are no different from inter-word saccades except lexical processing (L1 and L2) cannot begin until the word is located and attended to in (para)foveal vision. From this assumption (where word n is the line-initial word) we derive the following predictions:

1. Undersweep-fixations on word n+1 will not be terminated based on the lexical-frequency of word n+1.
2. If undersweep-fixations are terminated based on lexical processing it should be the lexical properties of the line-initial word (word n) that influence the duration of the undersweep-fixations on word n + 1.
3. Fixation times on line-initial words (n) would be reduced if preceded by an undersweep-fixation.

While our predictions suggest that attention will be on the line-initial word during an undersweep-fixation, we reasoned that if attention for word processing during an undersweep-fixation is on the fixated word, then there should be evidence of a spillover effect of frequency on the subsequent fixation or an effect of foveal load which would reduce the preview benefit of the line-initial word. These effects would manifest as longer fixations on line-initial words following an undersweep-fixation on low-frequency words. The foveal load hypothesis (Henderson & Ferreria, 1990) suggests that the processing difficulty of the fixated word modulates processing of the parafoveal word. Spillover effects (e.g. Kliegl, Nuthmann, & Engbert, 2006; White, 2008) posit that the processing of the previously fixated word delays or spills over to the processing of the fixated word. By examining these effects following an undersweep-fixation, it is possible to assess the allocation of attention during these brief fixations.

Since children's lexical knowledge develops over time, we assume that rates of lexical processing are slower in children (c.f. Reichle et al., 2013). Therefore, we may expect smaller subsequent benefits to skipping rates and gaze durations if lexical processing was driving these later facilitative effects reported in Slattery and Parker (2019). Furthermore, we would expect greater spillover effects following an undersweep-fixation in children due to their increased sensitivity to lexical properties of the fixated word. Finally, we expect that the parafoveal preview benefit for line-initial words which can be obtained during an undersweep-fixation (Parker & Slattery, 2019) will be smaller for children than adults as children are known to benefit less from such preview (e.g. Tiffin-Richards & Schroeder, 2015).

Analysis of Joseph et al. (2015)

To examine whether undersweep-fixations influence children's subsequent reading of a word, we first present a corpus analysis of Joseph et al. (2015). Joseph et al. recorded eye movements of 30 children (10-11 years-old) as they read multiline texts to investigate the time course of anaphor resolution. The nature of the experimental items provides an opportunity to analyse return-sweep behaviour in developing readers. Each of the 16 passages were formatted so that readers were required to make 3-6 return-sweeps to progress through the text. Text was single spaced displayed across 5.3 lines (range: 4-7), with each line extending from 29-68 characters (mean: 45.6 characters). Each sentence contained a mean of 7.9 words (range: 2-14), with a mean length of 4.2 characters (range: 1-12 characters). Word frequencies were acquired from the SUBTLEX-UK database (van Heuven, Mandera, Keuleers, & Brysbaert, 2014). The average Zipf frequency *(log10(frequency per million words) + 3)* of words across passages was 6.0 (range: 1.86-7.57) when using the children's CBBC measure of the SUBTLEX-UK.

Results

Fixations less than 80 ms within 1-character space of a previous or subsequent fixation were combined with that fixation. Other fixations shorter than 80 ms and greater than 1200 ms were excluded from the data set (0.37%). Trials in which there was excessive track loss (0.02%) or five or more blinks (0.06%) were also removed. Data for a single line was excluded if a blink or track loss preceded or followed a return-sweep. This led to data for 52 lines being excluded (0.09%).

First, we examined how lexical variables (frequency, length) influenced undersweep-fixation durations. To investigate whether information acquired during an undersweep-fixation informed subsequent reading, we examined two eye-movement measures: word skipping (the probability that the target word was skipped on first pass reading) and gaze duration (the sum of all first-pass fixations on the target word before moving to another word), while controlling for frequency, length, and launch site. Launch site refers to the distance (in characters) of the prior fixation from the currently fixated word and is a reliable predictor of fixation times and word skipping (e.g. Slattery, Staub, & Rayner, 2012) and is thought to index parafoveal processing. For words receiving undersweep-fixations, we calculated dependent measures by excluding undersweep-fixations. Therefore, a word that received an undersweep-fixation could still be considered "skipped" if it did not receive another fixation during the subsequent left-to-right pass. We restricted our analyses to the second, third, and fourth words on a line as this is where undersweep-fixations were most frequent (see Figure 1). For the purpose of all analyses we considered undersweep-fixations only when they were immediately followed by a leftwards saccade to a different word. We removed cases in which the corrective saccade leaving an undersweep-fixations was small enough to result in a refixation of the word (36.1% of undersweep-fixations). On average, these undersweep-fixations landed 6.9 characters from the start of the line (*SD*= 2.92). For all analyses, contrasts for undersweep-fixations were specified as −.5/.5 such that the intercept corresponded to the grand mean and the fixed effects corresponded to the main effects. All continuous fixed effects were centred.

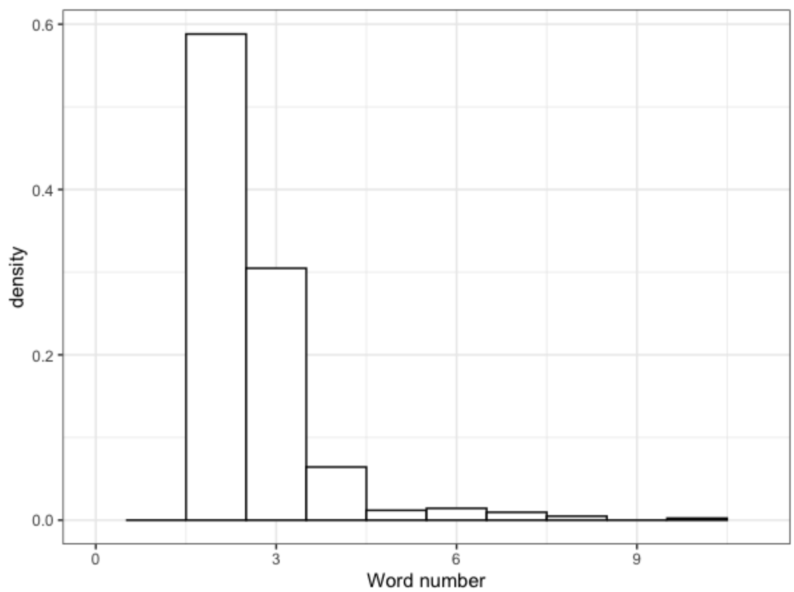

Figure 1. Histogram showing the distribution of undersweep-fixations as a function of word position on the line. The majority of undersweep-fixations occurred on words two, three, and four.

Eye movement data was analysed using Linear Mixed-effects Models (LMM) in the R computing environment (version 3.5.6., R Core Team, 2019) using the lme4 package (version 1.1-21; Bates, Maechler, Bolker, & Walker, 2015). We report regression coefficients (*b*), standard errors (*SE*), and *t*-values. We consider as statistically significant those cases where $|t| > 1.96$. For binary dependent variables such as word skipping we used generalised LMMs (glmer function from package lme4) and report Wald' *z*.

All models initially adopted the full random structure for both participants and word token, with random intercepts and slopes (Barr, Levy, Scheepers, & Tily, 2013). If models failed to converge, we fit a simplified random effects structure by removing parameters that were nearly or perfectly correlated with others so long as this did not reduce model fit (Bates, Kliegl, Vasishth, & Baayen, 2015). The number of observations and means of variables entering analysis are shown in Table 1. Data and R code is available on the Open Science Framework (https://osf.io/4rpba/).

Undersweep-fixation duration

The mean undersweep-fixation duration was 166.6 ms (*SD*= 49.32). The LMM fit to log-transformed undersweep-fixation duration included crossed random intercepts for participants and words: *lmer(dv ~ frequency + length + (1 | participant) + (1 | word).* Regression coefficients in Table 2 indicate that neither lexical-frequency nor word length influenced the duration of undersweep-fixations. We then examined the influence of line-initial word length and frequency on undersweep-fixation duration (*lmer(dv ~ line-initial word frequency + line-initial word length + (1 | participant) + (1 | word))*. The model indicated that neither line-initial word length, $b = -0.006$, $SE = 0.005$, $t = -1.37$, or frequency, $b = 0.004$, $SE = 0.007$, $t = 0.54$, influenced undersweep-fixation duration.

Based on these analyses, there is no evidence that undersweep-fixations were terminated based on lexical processing of the fixated word. To infer the extent to which our data reflect a null effect of lexical-frequency and word length, as opposed to a Type II error, we computed a Bayes Factor (Rouder, Morey, Speckman & Province, 2012) for the undersweep-fixation duration LMM with fixed effects of frequency and length, when compared to a denominator model that included random intercepts only. We computed the Bayes Factor in R using the BayesFactor package (v. 0.9.12-4.2; Morey & Rouder, 2018) with 100,000 Monte Carlo iterations. We assumed the default Cauchy prior for the effect size (see Abbott & Staub, 2015 for a discussion). The Bayes Factor for the original model when compared to the denominator model was 0.026. Based on Jeffrey's (1961) evidence categories for Bayes Factor, this provides strong evidence in favour of the denominator model that did not include lexical variables. The Bayes Factor for a model including line-initial word frequency when compared to the same denominator model was 0.215, indicating moderate evidence for the denominator model. This supports the conclusion that children's undersweep-fixations are not terminated on the basis of lexical properties of the fixated or the line-initial word.

Table 1. Study: Mean values of variables entering analyses.

	(G)LMM model		
	log Undersweep-duration	Word skipping likelihood	log Gaze duration
Observations analysed	402	2,414	2,004
Undersweep (%)	100	24.3	29.2
Frequency	5.3 (0.99)	5.7 (1.01)	5.08 (1.10)
Length	5.6 (1.63)	4.9 (1.30)	5.9 (1.84)
Launch site	.	4.1 (3.43)	5.3 (3.12)

Note. Standard deviations are shown in parentheses. Observations analysed refers to the number of data points entering the models. Undersweep percentage refers to the percentage of data points that are undersweep-fixations entering the models. Frequency refers to Zipf scores which are a logarithmic transformation of a word's occurrence in a given corpus where Zipf= *log10(frequency per million words) + 3*. Word length refers to the horizontal extent of a word in characters and launch site refers to the distance of the prior fixation from the fixated word (characters).

Table 2. Study: (G)LMM results for undersweep duration, word skipping, and gaze duration.

	log Undersweep duration			Word skipping likelihood			log Gaze duration		
Predictor	*b*	*SE*	*t*	*b*	*SE*	*z*	*b*	*SE*	*t*
Intercept	**2.211**	**0.014**	**160.24**	**-1.965**	**0.296**	**-6.630**	**2.418**	**0.017**	**141.14**
Undersweep	.	.	.	**1.626**	**0.185**	**8.789**	**-0.029**	**0.014**	**-2.08**
Frequency	-0.001	0.006	-0.22	**-0.403**	**0.073**	**-5.541**	**-0.016**	**0.007**	**-2.34**
Length	-0.002	0.004	-0.34	**0.461**	**0.105**	**4.396**	**0.019**	**0.003**	**5.52**
Launch site	.	.	.	**-0.198**	**0.026**	**-7.710**	**0.009**	**0.001**	**6.18**

Note. Significant terms are presented in **bold**.

Subsequent reading

Word skipping

The GLMM fit to word skipping included random intercepts for participants and words: *glmer(dv ~ undersweep + frequency + length + launch + (1 | participant) + (1 | word))*. From Table 2, word skipping was increased for shorter words, higher frequency words, and from near launch sites. There was also a main effect of undersweep-fixation, where skipping rates increased from 13.1% to 39.5% following an undersweep-fixation.

Gaze duration

The LMM fit to log-transformed gaze duration included random slopes for frequency across participants and a random intercept for word: *lmer(dv ~ undersweep + frequency + length + launch + (1 + frequency | participant) + (1 | word).* Gaze durations increased with increasing word length and increasing launch site. Gaze durations decreased with increasing word frequency. There was also a main effect of undersweep-fixation, where gaze durations decreased from 313.2 ms to 302.4 ms following an undersweep-fixation.

Discussion: Joseph et al. (2015)

It has long been assumed that undersweep-fixations which intervene a return-sweep and a corrective saccade are not involved in linguistic processing. However, Slattery and Parker (2019) reported that skilled adult readers were more likely to skip a word that had received an undersweep-fixation during a subsequent pass. Gaze durations during the left to right reading pass of the line were also shorter on words that had received an undersweep-fixation. In the present study we investigated whether children's eye movement records exhibit similar undersweep preprocessing benefits. Analysis revealed that, like adults, children aged 10-11 years-old were more likely to skip a word that had previously received an undersweep-fixation, and when later fixated the resulting gaze durations were shorter. This indicates that children may extract information from words occurring at the point of an undersweep-fixation that facilitates subsequent saccade targeting and encoding.

Yet, the precise nature of attention during an undersweep-fixation remains unclear. Analysis of the fixation duration after the corrective saccade provides an opportunity to examine the following possibilities: if attention was allocated to the fixated word during an undersweep-fixation there would be longer first-fixations on line-initial words following an undersweep-fixation on a low- relative to high-frequency word (i.e. spillover; e.g. Kliegl et al., 2006; White, 2008). Similarly, the parafoveal processing for a line-initial word would be reduced following an undersweep-fixation on a low- relative to -high-frequency word (i.e.

foveal load effect; Henderson & Ferreira, 1990). Evidence of these effects would indicate that attention necessary for lexical processing is allocated to the fixated word during an undersweep-fixation as opposed to the line-initial word (c.f. Parker & Slattery, 2019). These possibilities were examined in a sample of children ages 6-9 years-old to examine whether the undersweep preprocessing benefit could be observed in children who had less reading instruction. We tested these possibilities in a sample of adults in order to compare effects between adults and children in a single study.

Eye movement experiment

Method

Participants

Ninety-five participants (47 adults, 48 children) completed the current study. Children (23 male) were recruited from primary schools in Bournemouth and had a mean age of 7.5 years (*SD*= 0.85 years). Adults (15 male) were from Bournemouth University, and had a mean age of 21.0 years (*SD*= 2.66 years). All participants had normal or corrected-to-normal vision, were native English speakers, and were naïve to the purpose of the experiment. Furthermore, pre-screening with the Test of Word Reading Efficiency 2 (TOWRE; Torgesen, Wagner, & Rashotte, 2011) confirmed that all adults and children read at an age appropriate level (adults standard score: *M*= 109.8, *SD*= 11.15; children standard score: *M*= 109.2, *SD*= 13.26). Participants' general ability was assessed using two subtests of the Wechsler Abbreviated Scale of Intelligence II (WASI-II; Wechsler, 2011). Both groups performed at an appropriate level on the vocabulary (adults standard score: *M*= 54.3, *SD*= 8.76; children standard score: *M*= 53.8, *SD*= 10.80) and matrices subtests (adults standard score: *M*= 51.0, *SD*= 7.87; children standard score: *M*= 48.1, *SD*= 9.12). Children took part as unpaid volunteers and university students received course credits as a reward for participating.

Materials

Two sets of stimuli were developed, one appropriate for adults, the other appropriate for children. Experimental items consisted of one-to-two sentences over two lines with a high- or low-frequency target word being presented as the second word on the second line. For adult stimuli, line breaks extended from 41-48 characters (mean: 44.4 characters). For child stimuli, line breaks extended from 41-47 characters (mean: 43.5 characters). Text was double spaced for all participants. Word two of the second line was manipulated as our analysis of Joseph et al. (2015) indicated that undersweep-fixations were most likely to occur in this position. To increase the likelihood of participants landing on this target word, target words were medium to long in length (see Table 3). Target word length was controlled between groups with adults and children seeing target words of each length an equal amount. For children, low-frequency words had a significantly lower frequency of occurrence in the Children's Printed Word Database (Masterson, Stuart, Dixon, & Lovejoy, 2010), $t(39)= 9.07$, $p< .001$, $d= 2.00$, and a lower Zipf score based on frequency ratings from the SUBTLEX-UK database (Van Heuven, Mandera, Keuleers, & Brysbaert, 2014), $t(39)= 14.80$, $p< .001$, d= *3*.28, than did high-frequency words. For adults, low-frequency words had a significantly lower Zipf score based on frequency ratings from the SUBTLEX-UK database, $t(39)= 15.37$, $p< .001$, $d= 3.27$, than did high-frequency words. The mean word length of the line-initial words did not differ between the adult (*M*= 4.4-characters) and child stimuli (*M*= 4.4-characters), $t(78)= -.0.19$, $p= .854$, $d= -.04$. Stimuli were counterbalanced across participants. Each participant read 20 items in each condition (40 items in total), presented in a random order to each participant. Example stimuli are shown in Figure 2.

Table 3. Mean word length and frequency for high- and low-frequency target words.

	High-frequency				Low-frequency			
	Length	CPWD	CBBC Zipf	Zipf	Length	CPWD	CBBC Zipf	Zipf
Mean	7.7	222.9	4.7	4.7	7.7	7.5	3.3	3.1
Max.	10	830	5.6	5.5	10	27.0	3.9	4.0
Min.	6	105	4.0	4.1	6	3.0	2.3	1.2

Note. CPWD frequencies are given as the occurrence per million words. CBBC Zipf indicates frequency for the children's CBBC section of the SUBTLEX-UK corpus. Zipf indicates frequency for adults.

Group	Frequency	Stimuli
Children	High	The first thing Mary saw at the zoo was a funny ***elephant*** with big feet.
	Low	The first thing Mary saw at the zoo was a funny ***chipmunk*** with big feet.
Adults	High	Mary had fallen off the pavement. A group of four ***students*** rushed over to help her.
	Low	Mary had fallen off the pavement. A group of four ***hipsters*** rushed over to help her.

Figure 2. Example stimuli with the target word in ***bold***. Text was double spaced.

Apparatus

Passages were presented on a BenQ XL2410 T LCD with a 1920 by 1080 resolution, interfaced with a PC at a viewing distance of 80 cm. Passages were presented in black, Courier New, 22-point font on a white background; approximately three characters subtended 1° of visual angle. While viewing was binocular, eye movements were recorded from the right eye only using an EyeLink 1000 Plus tracker (S.R. Research Ltd.). Throughout the experiment, forehead and chin rests were used to minimise head movements. The spatial resolution of the eye tracker was 0.01°, and the sampling rate was 1,000 Hz.

Procedure

Off-line reading ability and IQ measures were completed first. Then, the eye movement experiment was conducted. Participants were instructed to read passages silently for comprehension. After each sentence, participants had to press a button on the keyboard to continue. Following 50% of the passages, participants answered a TRUE/FALSE comprehension question. Participants were free to take a break whenever they wished and could withdraw from the experiment at any point. Each participant read a total of 40 passages, which were embedded in a larger list of stimuli containing four practice passages and 20 fillers. The experimental session lasted approximately 20-30 minutes. Testing lasted approximately 1 hour.

Results

The mean comprehension accuracy was 82% for adults (range: 65-100%) and 81% for children (range: 58-100%). To examine whether comprehension scores differed between children and adults, we fit a GLMM to comprehension accuracy data. The model included fixed effects for participant group, experimental condition, and their interaction (*glmer(accuracy ~ frequency * group + (1 | participant) + (1 | item)*). On average, children's accuracy did not differ from adults, b= -0.093, SE= 0.153, z= -0.61. There was no main effect of frequency on adults' accuracy, b= 0.093, SE= 0.088, z= 1.06. The main effect of frequency did not differ between adults and children, b= -0.098, SE= 0.124, z= -0.79. Analysis of children's comprehension scores (*glmer(accuracy ~ frequency + (1 | participant) + (1 | item)*) confirmed that the manipulation of lexical-frequency did not influence their comprehension accuracy, b= -0.018, SE= 0.085, z= -0.21.

Fixations less than 80 ms within 1-character space of a previous or subsequent fixation were combined with that fixation. Other fixations shorter than 80 ms and greater than 1200 ms were excluded from the data set. Trials in which there was excessive track loss or five or more blinks were also removed. Data for a single line was excluded if a blink or track loss preceded or followed a return-sweep, as were trials in which there was a blink or track loss on the target word or an immediately adjacent fixation. Data trimming procedures removed 1.96% of trials from analysis.

We present five sets of analyses. The first explores the impact of development and lexical-frequency on undersweep-fixation duration. The second explores the influence of development and undersweep-fixations on a reading pass through the line. The third examines whether there is inhibition of return (IoR) to the location of undersweep-fixations. The fourth examines whether the amount of pre-processing on line-initial words is reduced following an undersweep-fixation on a low- relative to high-frequency word. The fifth examines whether spillover effects are observed following an undersweep-fixation on a high- relative to low-frequency word. Analyses one and two examined fixation behaviour on target words (i.e. the second word on the line). Analysis three compared intra-line fixations with those on line-initial words when the target word had been fixated on the prior fixation. Analyses four and five examined fixation behaviour on line-initial words (i.e. words to the left of the target). For all analyses we consider undersweep-fixations when they landed on the target word and followed by an immediate leftwards saccade to a new word. This led to the removal of cases in which undersweep-fixations were followed by an immediate refixation (35.4% of cases for adults, 44.6% of cases for children). On average, adults' undersweep-fixations landed 6.3 characters (*SD*= 1.73) from the start of the line. This was comparable to children's undersweep landing positions (mean= 6.4, *SD*= 2.03).

Reading time measures were analysed using LMMs with participants and items as crossed random intercepts. All models initially included the full random structure. However, if models failed to converge the pruning conventions described above were applied. For our analysis of word skipping, data were analysed using a generalized linear model with the glm function as the random intercepts only GLMM failed to converge. Because skilled adult reading represents the end point of reading development, we used adult data as the baseline (intercept) for all models. Thus, contrasts for participant group were specified as 0/1. All other contrasts were specified as −.5/.5, such that the intercept corresponded to the grand mean of adults and the fixed effects corresponded to the main effects. We supplement our analyses with identical models fit to children's data. For models in which critical null effects of lexical-frequency were observed, we computed Bayes Factors following the conventions as reported previously[1].

Undersweep-fixation duration

The percent of return-sweeps followed by an undersweep-fixation did not differ between adults (28.5%) and children (28.9%), b= 0.021, SE= 0.075, z= 0.28. The average undersweep-fixation duration was 172.4 ms for adults and 162.7 ms for children (see Figure 3). Test statistics for the LMM fit to log-transformed undersweep-fixation data (*lmer(dv ~ frequency * group + (1 + frequency | participant) + (1 + frequency | item))* are shown in Table 4. Adults' undersweep-fixation durations did not differ between frequency conditions. While children's undersweep-fixations were shorter than adults', the effect of frequency did not differ between adults and children. The Bayes Factor for a model including frequency compared to a denominator model in which frequency was removed was <0.001. This is taken as extreme evidence for the null hypothesis that undersweep-fixation duration was uninfluenced by lexical-frequency. Analysis of children's data confirmed no effect of lexical-frequency on undersweep-fixation durations in children (see Table 5).

We then examined the influence of line-initial word frequency (centred about its mean) on undersweep-fixation in both adults and children *(lmer(dv ~ line-initial word frequency * group + (1 | participant) + (1 | word))*. The model indicated that line-initial word frequency did not influence adults' undersweep-fixation durations, b= -0.008, SE= 0.008, t= 1.09. While children's undersweep-fixations were shorter, b= -0.032, SE= 0.014, t=

-2.24, the effect of line-initial word frequency did not differ for children, b= 0.014, SE= 0.010, t= 1.39. The Bayes Factor for a model including line-initial word frequency compared to a denominator model in which line-initial word frequency was removed was <0.001. Examination of children's data indicated confirmed no effect of line-initial word frequency on undersweep-fixation duration, b= 0.007, SE= 0.007, t= 0.96.

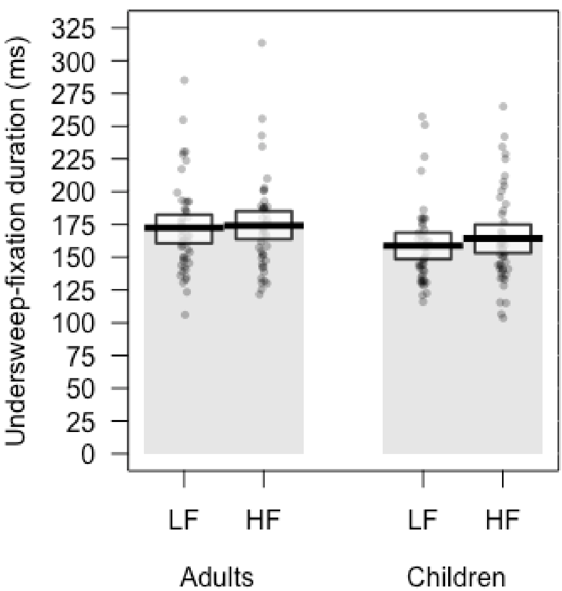

Figure 3. Pirate plot showing the mean undersweep-fixation duration on target words for adults and children in the high- and low-frequency conditions. The central tendency is the mean (black line) and the intervals are 95% Confidence Intervals. Points show the mean undersweep-fixation duration for each participant.

Table 4. Experiment: Logistic regression and LMM results for undersweep-fixation durations *(998 observations)* and subsequent word skipping *(3,508 observations)* and gaze duration *(3,053 observations)*.

	log Undersweep duration			Word skipping likelihood			log Gaze duration		
Predictor	*b*	*SE*	*t*	*b*	*SE*	*Z*	*b*	*SE*	*t*
Intercept	**2.224**	**0.010**	**212.09**	**-1.207**	**0.064**	**-18.74**	**2.390**	**0.020**	**119.43**
Group (Child)	**-0.031**	**0.015**	**-2.07**	**-1.797**	**0.150**	**-12.00**	**0.233**	**0.028**	**8.32**
Undersweep	.	.	.	**2.067**	**0.129**	**16.04**	**-0.121**	**0.014**	**-8.37**
Frequency	0.001	0.009	0.05	**0.391**	**0.129**	**3.03**	**-0.094**	**0.014**	**-6.86**
Group X Undersweep	.	.	.	-0.065	0.299	-0.22	**0.057**	**0.019**	**2.99**
Group X Frequency	0.004	0.013	0.31	0.517	0.299	1.73	**-0.073**	**0.018**	**-4.05**
Undersweep X Frequency	.	.	.	0.158	0.258	0.62	-0.012	0.028	-0.45
Group X Undersweep X Frequency	.	.	.	0.555	0.599	0.93	0.012	0.036	0.33

Note. Significant terms are presented in **bold**.

Table 5. Experiment: Logistic regression and LMM results children's undersweep-fixation durations *(475 observations)* and subsequent word skipping *(1,664 observations)* and gaze duration *(1,577 observations)*.

	log Undersweep duration			Word skipping likelihood			log Gaze duration		
Predictor	*b*	*SE*	*t*	*b*	*SE*	*z*	*b*	*SE*	*t*
Intercept	**2.193**	**0.011**	**208.58**	**-3.004**	**0.135**	**-22.22**	**2.622**	**0.024**	**110.87**
Undersweep	.	.	.	**2.002**	**0.270**	**7.40**	**-0.064**	**0.014**	**-4.72**
Frequency	0.004	0.009	0.48	**0.907**	**0.270**	**3.36**	**-0.167**	**0.013**	**-13.33**
Undersweep X Frequency	.	.	.	0.713	0.541	1.32	-0.001	0.025	-0.03

Note. Significant terms are presented in **bold**.

Subsequent reading

Word skipping

We fit a GLM model to word skipping likelihood: *glm(dv ~ frequency * undersweep * group)*. From Figure 4, adults showed main effects of frequency and undersweep likelihood where skipping was increased for high-frequency words and words receiving an undersweep-fixation. The frequency by undersweep interaction did not significantly impact skipping rates. Relative to adults, children were less likely to skip words. The remaining interactive terms did not significantly impact skipping likelihood, indicating that the frequency effect and undersweep pre-processing benefit did not differ between adults and children. From analysis of the children's data it is evident that, like adults, children are more likely to skip a word if it had previously received an undersweep-fixation. They were also more likely to skip high-frequency words. Like adults', children's skipping was not modulated by the frequency by undersweep interaction.

Gaze duration

The LMM fit to log-transformed gaze duration included random intercepts only: *lmer(dv ~ frequency * undersweep * group + (1 | participant) + (1 | item)*. For adults, there were main effects of frequency and undersweep likelihood indicating that adults gaze durations were shorter on high-frequency words and those that had previously received an undersweep-fixation. The frequency by undersweep interaction did not impact gaze durations. The simple effect of age group indicated that children's gaze durations were longer than adults'. The interaction between group and frequency suggested that frequency effects were larger for children. The group by undersweep interaction indicated that, relative to adults, children showed a weaker undersweep pre-processing advantage[2]. Like adults', children's gaze durations were not modulated by the interaction between frequency and undersweep. From the children's data, gaze durations were shorter on high-frequency words, and those previously fixated during an undersweep-fixation. The interactive term did not significantly impact children's gaze durations. The combination of analyses indicates that while children are able to extract information during an undersweep-fixation that facilitates later encoding, they are not as efficient as adults at doing this.

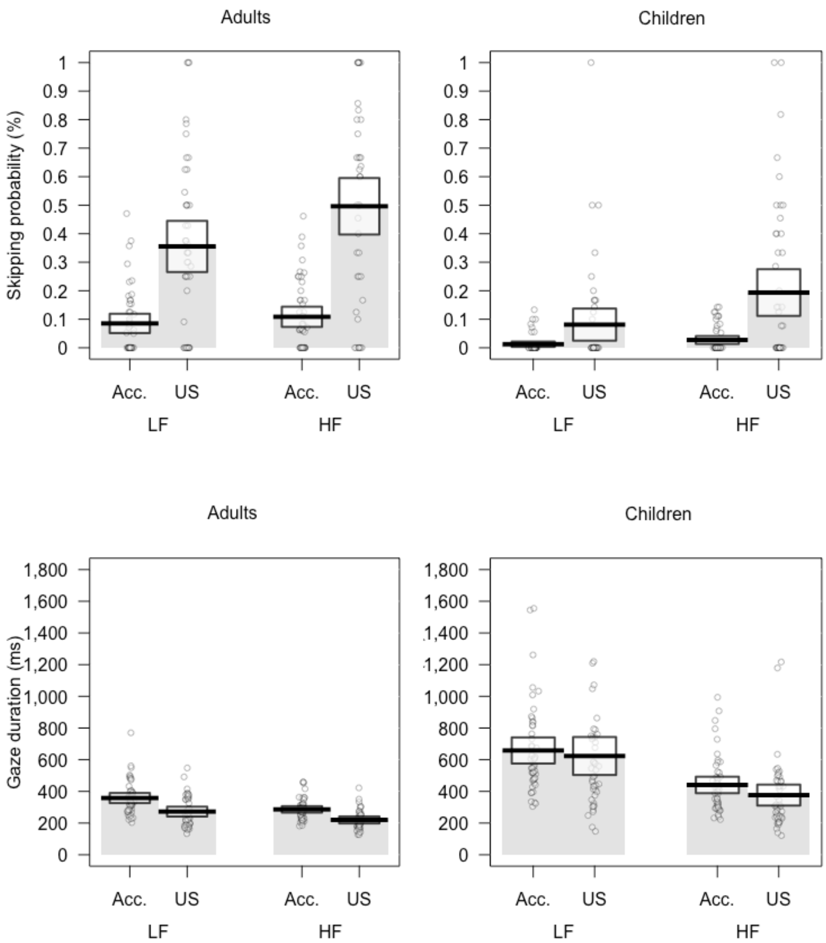

Figure 4. Pirate plot showing the mean skipping probability and gaze duration on target words for adults and children in the high- and low-frequency conditions. For word skipping Acc shows cases in which the target word did not receive an undersweep-fixation. For gaze duration Acc shows cases were target words were initially fixated during a rightwards pass. For both word skipping and gaze duration, US shows cases where the target was fixated following an undersweep-fixation. The central tendency is the mean (black line) and the intervals are 95% Confidence Intervals. Points shows participant means.

Inhibition of return

Given reports of IoR effects following undersweep-fixations (Slattery & Parker, 2019), we examined the extent to which increased skipping rates and shorter gaze durations following an undersweep-fixation may be related to IoR. This was achieved by comparing fixation durations prior to a rightwards saccade to a new word (i.e. skipping the previously fixated word) to those preceding a saccade to a word that had been fixated on the immediately prior fixation. We examined this comparison for both intra-line fixations (the intercept) and those following undersweep-fixations in both age groups. Following prior investigations of IoR effects in reading (Rayner, Juhasz, Ashby, & Clifton, 2003; Slattery & Parker, 2019), we limited our analyses to cases where the saccade length was between 3- and 12-characters and statistically controlled for saccade length in analysis *(lmer(dv~ forwards return * undersweep * group + saccade length + (1 | participant) + (1 | word))*. As the frequency by undersweep interaction did not influence skipping or gaze durations we did not include frequency in the model to avoid model overparameterization. For adults, there were main effects of skipping and undersweep likelihood such that fixations were shorter prior to a forward skip of a previously fixated word and longer when following an undersweep-fixation than for intra-line case (see Table 6). The interaction did not impact adults' fixation durations. The simple effect of group indicated that children's fixations were longer than adults'. The remaining interactive terms did not significantly impact skipping likelihood, indicating that the main effects and interaction did not differ between adults and children. Analysis of children's data confirmed main effects of skipping and undersweep-fixations, and an absence of an interaction (see Table 7).

Table 6. Experiment: LMM results for Inhibition of Return (IoR) analysis *(11,040 observations).*

	log-Fixation duration		
Predictor	*b*	*SE*	*t*
Intercept	**2.315**	**0.016**	**143.55**
Group (Child)	**0.181**	**0.022**	**8.32**
Forwards skip (FS)	**-0.052**	**0.015**	**-3.54**
Undersweep-fixation (US)	**0.041**	**0.016**	**2.60**
Saccade length	**0.010**	**0.003**	**3.31**
Group x FS	0.007	0.022	0.31
Group x US	0.010	0.021	0.45
US x FS	0.035	0.027	1.30
Group x FS x US	-0.037	0.041	-0.92

Table 7. Experiment: LMM results for children's Inhibition of Return (IoR) analysis *(2,636 observations).*

Children: Forward return saccades vs. forward skip saccades: 2,636 observations			
Predictor	*b*	*SE*	*t*
Intercept	**2.497**	**0.020**	**124.09**
Forwards skip (FS)	**-0.045**	**0.017**	**-2.58**
Undersweep-fixation (US)	**0.053**	**0.017**	**3.03**
Saccade length	**0.013**	**0.005**	**2.74**
US x FS	-0.004	0.033	-0.13

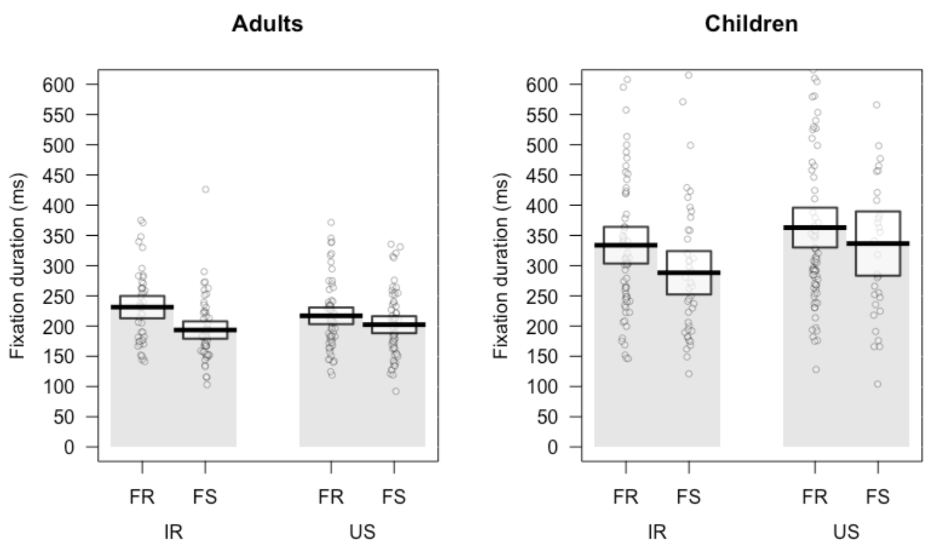

Figure 3. Pirate plot showing the mean fixation durations prior to forwards returns (FR) and forwards skips (FS) for intra-line and undersweep cases for adults and children. The central tendency is the mean (black line) and the intervals are 95% Confidence Intervals. Points show the mean fixation duration prior to the skipping or return saccade for each participant.

Preview for line-initial words.

To assess our prediction that fixation times on line-initial words should be reduced if preceded by an undersweep-fixation, we compared cases in which readers fixated line-initial words accurately following a return-sweep with those in which readers fixated line-initial words following an undersweep-fixation. The model fit to log-transformed gaze duration, (*lmer(dv ~ undersweep * frequency * group + (1 + undersweep | participant) + (1 | item)*) indicated a main effect of undersweep where adults' gaze durations on line-initial words were shorter following an undersweep-fixation (see Table 8). Yet the main effect of frequency and its interaction with undersweep did not impact adult's gaze duration. The simple effect of age group indicated that children's gaze durations were longer than adults'. While the main effect of frequency did not differ between age groups, the main effect of undersweep did, indicating that children showed a smaller reduction in gaze duration on line-initial words following an undersweep-fixation. The remaining interactive terms did not modulate gaze durations. Our analysis of children's data confirmed that gaze durations were shorter on line-initial words following an undersweep-fixation than if it had been fixated following a return-sweep (see Table 9). Again, there was no influence of frequency or its interaction with undersweep on gaze durations confirming that the lexical-frequency of the second word on a line (n+1) did not modulate children's gaze durations on the line-initial word (n). Subsequent Bayes Factor analysis favoured a model in which frequency was removed by 0.005 suggesting extreme evidence for the null hypothesis that readers' gaze durations on line-initial words are not modulated by the lexical-frequency of a word receiving an undersweep-fixation (see Figure 5).

Table 8. Experiment: LMM results for preview for line-initial word (word n) *(2,859 observations)* and spillover analyses *(1,097 observations)*.

	Preview (log Gaze duration)			Spillover (log-first fixation duration)		
Predictor	*b*	*SE*	*t*	*b*	*SE*	*t*
Intercept	**5.577**	**0.044**	**127.64**	**2.307**	**0.014**	**166.40**
Group (Child)	**0.406**	**0.061**	**6.64**	**0.136**	**0.020**	**6.91**
Undersweep	**-0.238**	**0.029**	**-8.24**	.	.	.
Frequency n+1	0.002	0.024	0.09	-0.022	0.015	-1.52
Group X Undersweep	**0.122**	**0.040**	**3.01**	.	.	.
Group X Frequency n+1	-0.049	0.034	-1.46	0.005	0.021	0.22
Undersweep X Frequency n+1	-0.071	0.039	-1.84	.	.	.
Group X Undersweep X Frequency n+1	0.090	0.055	1.64	.	.	.

Note. Significant terms are presented in **bold**.

Table 9. Experiment: LMM results for children's preview for line-initial word (word n) *(1,461 observations)* and spillover analyses *(532 observations)*.

	Preview (log Gaze duration)			Spillover (log-first fixation duration)		
Predictor	*b*	*SE*	*t*	*b*	*SE*	*t*
Intercept	**2.598**	**0.023**	**114.26**	2.443	0.015	162.013
Undersweep	**-0.050**	**0.014**	**-3.60**	.	.	.
Frequency n+1	-0.020	0.011	-1.88	-0.018	0.016	-1.167
Undersweep X Frequency n+1	0.009	0.018	0.46	.	.	.

Note. Significant terms are presented in **bold** .

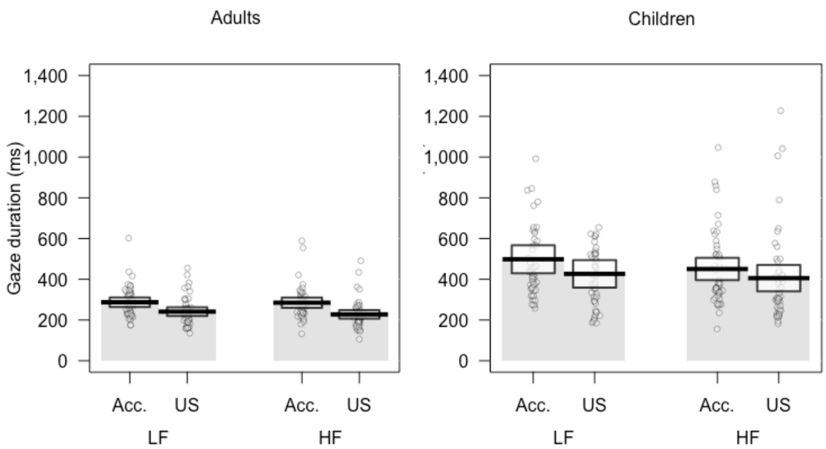

Figure 5. Pirate plot showing and gaze durations on line-initial words for adults and children in the high- and low-frequency conditions. Acc shows cases in which readers return-sweeps landed on the line-initial word. US shows cases where the line-initial words were fixated following an undersweep-fixation. The central tendency is the mean (black line) and the intervals are 95% Confidence Intervals. Points shows the gaze duration for each participant.

Spillover

Here we assess our prediction that if attention for word processing during an undersweep-fixation is on the fixated word, then there should be evidence of a frequency spillover effect. For this analysis, we considered line-initial words (n) only when an undersweep-fixation had been made on a target word (n +1) immediately before fixating a line-initial word. The model fit to log-transformed first-fixation duration (*lmer(dv ~ frequency * group + (1 | participant) + (1 + frequency | item))*, indicated no main effect of frequency for adults (see Table 8). While children's first fixations on line-initial words were longer than adults', the main effect of frequency did not differ between adults and children. Analysis of children's data confirmed no main effect of word n+1 frequency on the fixation following an undersweep-fixation (see Table 9). Bayes Factor analysis favoured a model in which frequency was removed the model by a factor of 0.001. This is considered extreme evidence for the null hypothesis. Together, these findings suggest that there was no spillover from an undersweep-fixation in first-fixation duration on line-initial words (see Figure 6).

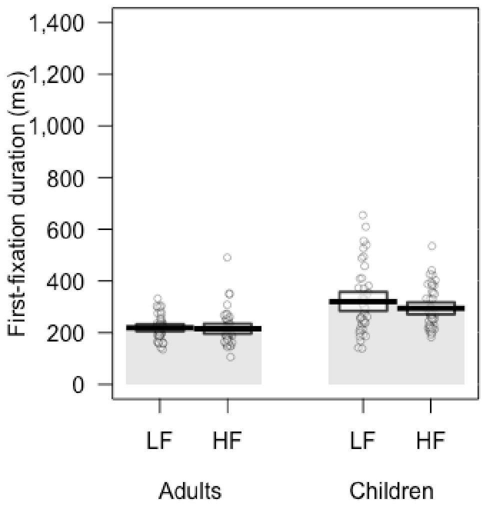

Figure 6. Pirate plot showing the first-fixation durations on line-initial words target words for adults and children in the high- and low-frequency conditions. The central tendency is the mean (black line) and the intervals are 95% Confidence Intervals. Points show the first-fixation duration on linr-initial words for each participant.

Discussion: Eye movement experiment

In the present experiment we examined how the lexical-frequency of words receiving an undersweep-fixation influences adults' and children's fixation behaviour as they begin their subsequent pass across the line. First, while children's undersweep-fixation durations were shorter than adults', we report that the duration of the undersweep-fixation did not differ for high- or low-frequency target words. Second, we report that both adults and children were more likely to skip words that had received an undersweep-fixation prior to a rightwards pass. When words that had previously received an undersweep-fixation were fixated during the rightwards pass of the line, the resulting gaze durations were shorter. This reduction in gaze duration was statistically smaller for children. The lexical-frequency of words receiving an undersweep-fixation did not attenuate these skipping or gaze duration effects. Third, we found evidence for IoR effects in both adults and children suggesting that increased skipping rates following an undersweep-fixation could reflect an avoidance in redeploying attention to a previously fixated location. Although, the contribution of IoR to reduced gaze durations is a little less clear. Fourth, we report that gaze durations on line-initial words were shorter when preceded by an undersweep-fixation. Again, this effect was statistically smaller for children. Fifth, we found that, following an undersweep-fixation, there was no evidence of spillover on line-initial words. Together these results shed light on the nature of attention during undersweep-fixations suggesting that readers may first deploy attention to the fixated word (as indicated by IoR effects) prior to redeploying attention to the line-initial word. We discuss the implications of these results for development and modelling in the General Discussion.

In addition to our novel findings, we found significant effects of lexical-frequency on word skipping and fixation times in both adults and children during a rightwards pass through the text. The effect of lexical-frequency was potentially stronger for children as indexed by the interaction between participant group and lexical-frequency in readers' gaze durations. This finding is consistent with prior work (Blythe et al., 2009; Joseph et al., 2013; Tiffin-Richards & Schroeder, 2015). While our decision to use age-appropriate stimuli enabled us to maintain processing difficulty of the target word across age groups, analysis of age-group effects was between-items (c.f. Blythe & Joseph, 2011). As a result, differences between groups in terms of lexical-frequency and undersweep processing may have been attributable to participant age, or slight differences in the items being read rather than developmental changes. So, at the very least, we can conclude that both adults and children exhibit clear frequency effects and are capable of extracting information at the point of, and to the left of, fixation that facilitates subsequent encoding.

General discussion

There is a wealth of empirical and computational research on various oculomotor and linguistic aspects of eye-movement control during silent reading in adults. In comparison, literature on children's eye movements during silent reading is rather sparse. For both adults and children, few studies have investigated return-sweep saccades. Rather than focus on the return-sweep itself, the current work examined the commonly occurring fixation that results from return-sweep undershoot error and is immediately followed by a corrective saccade. Specifically, we considered its contribution to lexical processing during children's subsequent reading pass across a line. The contribution of this work can be summarised in four general points. First, we extended the existing literature on children's eye movements in reading. Second, we showed that children's undersweep-fixations are not terminated on the basis of lexical processing for the fixated word. Third, we reported that children are able to acquire information during an undersweep-fixation that influences their subsequent pass through the text. Fourth, we show that, like adults, children partially process line-initial words during an undersweep-fixation.

E-Z Reader assumes that readers gain access to information about a word for lexical processing once it is attended in parafoveal vision. For the processing of information at the very start of the line, we assumed that the shift in attention to this location is dependent on return-sweep execution. That is, lexical processing for line-initial words cannot commence until the word is available in (para)foveal vision. With this assumption (where the line-initial word is word n), we predicted:

1. Undersweep-fixations on word n+1 will not be terminated based on the lexical-frequency of word n+1.
2. If undersweep-fixations are terminated based on lexical processing it should be the lexical properties of the line-initial word (word n) that influence the duration of the undersweep-fixations on word n + 1.
3. Fixation times on line-initial words (n) would be reduced if preceded by an undersweep-fixation.

While we predicted that attention would be on the line-initial word during an undersweep-fixation, we reasoned that if attention was instead allocated to the fixated word then there would be longer first-fixations on line-initial words following an undersweep-fixation on a low- relative to high-frequency word (i.e. spillover; e.g. Kliegl et al., 2006). Similarly, we reasoned that the parafoveal processing of a line-initial word would be reduced following an undersweep-fixation on a low- relative to -high-frequency word (i.e. foveal load effect; Henderson & Ferreira, 1990). In terms of developmental differences, any assumption of lexical processing during an undersweep-fixation, whether it be for word n or n+1, would predict longer undersweep-fixation durations in children. Below, we relate the data back to these predictions.

Consistent with prediction 1, undersweep-fixations were not terminated based on the lexical-properties of the word at the point of fixation. Bayes Factor analysis demonstrated that there is strong evidence for the null supporting this conclusion. If, as predicted, attention is allocated towards the line-initial word, then we might expect to observe an influence of line-initial frequency on undersweep-fixation duration. With regards to prediction 2, we found no evidence of line-initial word frequency influencing undersweep-fixation duration in either dataset. While this is inconsistent with our prediction derived from E-Z Reader, we feel the model can adequately explain this via the mislocated fixation account. Within E-Z Reader, fixations that land far from their target will trigger a corrective saccade program to a more optimal location. So, while readers may allocate attention necessary for linguistic processing to the line-initial word, L1 may not complete prior to the oculomotor system executing the non-labile stage of a corrective saccade. What is most interesting is that children's undersweep-fixations were shorter than adults'. If children were engaged in lexical processing during an undersweep-fixation, then one might assume that their undersweep-fixations would be longer than adults'. This clearly argues against lexical processing terminating these fixations. It instead appears that these differences may reflect an increased sensitivity to retinal feedback following a return-sweep where children will more rapidly execute a fixation towards a line-initial word to foveally encode information in that location (c.f. Parker, Slattery, & Kirkby, 2019).

Assuming that attention is located on the line-initial word would predict that lexical processing should not occur for words receiving an undersweep-fixation until they are directly fixated during the rightwards pass. Yet, we report that both adults and children are able to acquire some meaningful information at the point of an undersweep-fixation that influences their subsequent fixations across the line—though these effects are statistically smaller for children. Given that there was no spillover observed when fixating a line-initial word following an undersweep-fixation on a low- relative to high-frequency word, we concluded that readers are not lexically processing this information. Instead, IoR effects suggest that readers allocate their attention to the fixated word before redeploying attention to the left (i.e. the line-initial word). The level of attention given to the undersweep-fixated word is likely to be pre-lexical. Therefore, like Slattery and Parker (2019), we argue that readers acquire preattentive letter identity information sufficient to facilitate later lexical processing. Models of word recognition suggest that prior to lexical access on a word, readers first recognise words in parts (letters) independently of word context (see Carreiras, Armstrong, Perea, & Frost, 2014, for a review). Assuming a model such as the SERIOL model (Whitney, 2001), this speculation would suggest that readers' open bigram nodes are activated by visual input prior to executing the corrective saccade such that if an undersweep-fixation were made on the word *rock* (word n+1) this orthographic input would activate nodes that present the relative position of within word letter pairs such as *rc*, *ro*, and *ck*. These open bigram nodes would then remain active across multiple fixations thus facilitating sequent encoding. For cases of skips readers would use this information parafoveally when fixating word n. When word n+1 is later fixated during the rightward pass, this information would aid subsequent encoding as letter the nodes necessary for encoding remain active and enable the reader to quickly move on to a later point in word recognition. These facilitative effects parallel those reported in the masked priming paradigm where orthographically related primes facilitate the identification of target words (for a discussion see Kinoshita, Gayed, & Norris, 2018).

While it may, in principle, be easier for a parallel processing architecture like SWIFT to account for the undersweep preprocessing benefit, E-Z Reader may be able explain these findings. Within E-Z Reader there is a preattentive stage (*V*) during which information is processed in parallel across the visual field irrespective of where attention is allocated (Reichle, Rayner, & Pollatsek, 2012). The preattentive stage makes two types of information available: low spatial-frequency information corresponding to word boundaries that is used for saccade target selection and coarse orthographic details such a letter forms necessary for lexical processing. E-Z Reader may then predict that readers would acquire letter forms and word length information capable of influencing later saccade targeting. Following E-Z Reader, it may also be that readers acquire information from undersweep-fixations that promotes saccade targeting to be more optimal during a subsequent pass. Further research is required to explore these effects.

Finally, we predicted that undersweep-fixations would provide the opportunity for readers to acquire preview from line-initial words. Here the evidence is clear. Consistent with prediction 3, we report that, identical to Parker and Slattery (2019), adults' gaze durations on line-initial words were shorter when preceded by an undersweep-fixation than when the return-sweep landed on these words without such intervening pauses. The current experiment extends previously reported findings in suggesting that these gaze duration benefits may be reduced for children. Given previous reports of reduced parafoveal pre-processing in children relative to adults (Tiffin-Richards & Schroeder, 2015), it is not surprising that such an interaction was observed. However, what is surprising is that these effects exist when children are not lexically processing the fixated word. Therefore, it seems that when an undersweep-fixation lands on word n+1, prelexical attention is briefly allocated to the point of an undersweep-fixation (explaining IoR effects and low-level feature extraction). Upon realising that return-sweep landed incorrectly, attention is shifted toward the line-initial word (n) and the oculomotor system programmes at saccade towards this word. At this point, processing of word n begins prior to direct fixation[3]. Readers' flexibility in using information to the left of fixation is by no means a novel observation. In a study where a moving window was used to mask all words to the right of fixation, Roy-Charland et al. (2012) reported that readers were able to detect a target within a word that was unmasked after being skipped, indicating that readers use information to the left of fixation. The argument of rapid deployment of attention following an undersweep-fixation is similar for mislocated fixations (Drieghe, Rayner, & Pollatsek, 2008) and is based on the decoupling of attention and fixation location due to oculomotor error. Though it is critical to note here that the mislocated fixation account within the E-Z Reader framework would predict no error in the allocation of attention. However, since E-Z Reader was developed to simulate single line reading, it never faced the magnitude of saccadic error that occurs with return-sweeps.

Simulations using the E-Z model suggest that differences in rates of lexical processing are sufficient for explaining a majority of developmental differences between adults and children. Consistent with this explanation we found longer fixation durations and lower skipping rates in children relative to adults. Our novel findings are in keeping with such an explanation. First, children and adults do not differ in their ability to deploy attention that is necessary for lexical processing in a strictly serial manner during reading as indexed by both groups showing shorter gaze durations on line-initial words following an undersweep-fixation. What is surprising, however, is that children have learned to utilise information projected onto the fovea as a result of oculomotor error in a similar manner to adults following little reading instruction. Indeed, children as young as 6 years-old show increased skipping rates and shorter gaze durations on words previously receiving an undersweep-fixation indicating that they can make use of these oculomotor errors to produce a more efficient reading pass of the line. What is most striking is that this information facilitates skipping equally across age groups. The differences in gaze duration reduction following an undersweep-fixation may reflect children's need to acquire additional information to offset their increased sensitivity to linguistic properties of the fixated word. In the context of open bigrams, it may be that children would need to fixate words for longer for bigram nodes to activate and lead to a similar reduction in gaze durations as adults. It is alternatively possible that as children spend longer on line-initial words the nodes become less active and when they later fixate them on the rightward pass they must start from an earlier point in decoding compared to adults. We would like to make it clear that these suggestions are speculative and further research is required to form any firm conclusion.

Conclusion

The current research extends what we currently know about adults' and children's eye movements during the reading of multiline texts. Adults' and children's undersweep-fixations, which result from return-sweep undershoot error, are not terminated by lexical properties of the text indicating that they are not under direct cognitive control. When readers make these erroneous fixations, they first allocate their attention to the point of an undersweep-fixation—as indicated by IoR effects—prior to rapidly redeploying their attention towards the line-initial word. Prior to the redeployment of attention, during a preattentive stage of processing, both adults and children extract information at the point of fixation that facilitates later processing of that word. As soon as attention shifts to the line-initial word, adults and children begin processing information in that location. This strikingly similar pattern of effects between adults and children strongly indicates that the mechanisms controlling for oculomotor coordination and attention necessary for reading across line boundaries are established from a very early point in reading development.

Notes

1. Power simulations suggested that a sample of 95 readers was sufficient to detect the main effects and the critical undersweep by frequency interaction in subsequent gaze duration analysis, other analyses may have had low statistical power for detecting small effects. Hence our decision to supplement our NHST models with Bayes Factor analysis. Additionally, we ran an omnibus test for each dependent measure using the ezANOVA function within the ez package, to examine main effects of our experimental manipulations and interactions. For the sake of parsimony, we only do not report these in full as the pattern of effects was generally consistent with our LMM models.
2. We subsequently examined refixations rates following an undersweep-fixation. Adult's refixation rates on target words reduced from 35.4% to 15.8%. Children's refixation rates reduced from 53.8% to 41.1%. A GLMM fit to refixation likelihood *(glmer(dv ~ undersweep * group + (1 | participant))* indicated that children were more likely to require refixations on target words. A main effect of undersweep indicated that fewer refixations were required following an undersweep-fixation, yet this effect was reduced for children. Thus, differences in gaze duration reductions following an undersweep-fixation between age groups may partially reflect adults' ability to more efficiently target saccades when returning to a previous fixated word.
3. In both datasets, it would seem that readers do not acquire preview for the word to the right of an undersweep-fixation. A model fit to Joseph et al.'s (2015) data which included a variable coding whether an undersweep-fixation had occurred on a word to the left of fixation *(lmer(dv ~ undersweep + (1 | participant) + (1 | word))* indicated no effect of the categorical predictor on log-transformed gaze duration, $b = 0.008$, $SE = 0.011$, $t = 0.76$. We also fit a model to log-transformed gaze durations for words to the right of experimental target words that included fixed effects for participant group, a categorical predictor coding whether an undersweep had occurred on a given line, and the interaction: *lmer(dv ~ frequency * undersweep * group + (1 + frequency | participant) + (1 | item)*. While mean gaze duration differed between adults and children, $b = 0.145$, $SE = 0.028$, $t = 5.12$, there was no main effect of undersweep-likelihood for adults, $b < 0.001$, $SE = 0.012$, $t = 0.02$, and this did not differ for children, $b = -0.015$, $SE = 0.018$, $t = -0.87$. This supports the claim that the usual righthand skew of parafoveal attention is shifted to the left during an undersweep-fixation duration.

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