Do readers use character information when programming return-sweep saccades?

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Abstract

Reading saccades that occur within a single line of text are guided by the size of letters. However, readers occasionally need to make longer saccades (known as return-sweeps) that take their eyes from the end of one line of text to the beginning of the next. In this study, we tested whether return-sweep saccades are also guided by font size information and whether this guidance depends on visual acuity constraints. To do this, we manipulated the font size of letters (0.29 vs 0.39º per character) and the length of the first line of text (16 vs 26º). The larger font resulted in return-sweeps that landed further to the right of the line start and in a reduction of corrective saccades compared to the smaller font. This suggests that font size information is used when programming return-sweeps and corrective saccades. Return-sweeps in the longer line condition landed further to the right of the line start and the proportion of corrective saccades increased compared to the short line condition. This likely reflects an increase in saccadic range error with the increase in saccade size. Critically, however, there was no interaction between font size and line length. This suggests that when programming return-sweeps, the use of font size information does not depend on visual acuity at the saccade target. Instead, it appears that readers rely on global typographic properties of the text in order to maintain an optimal number of characters to the left of their first fixation on a new line.

Keywords: reading, eye-movements, font size, saccade planning, return-sweeps

Word count: 249 words

Return-sweeps are the largest saccades during reading. Their function is to move gaze from the end of one line of text to the beginning of the next (Rayner, 2009). While return-sweeps are common in everyday reading, their planning is not well understood as most eye-movement studies of reading have used single-line sentences where return-sweeps are absent. Consequently, it is unclear whether return-sweeps and saccades that occur within a single line (i.e. intra-line saccades) are guided by the same oculomotor principles. For example, intra-line saccades are guided by the number of characters they travel rather than some relative distance in degrees per visual angle (Morrison & Rayner, 1981; O'Regan, 1983). However, as return-sweeps traverse a much larger distance, it is not clear if character information is as reliable a targeting cue. Here, we investigated whether return-sweeps are guided by character information like intra-line saccades, and whether the use of such information is modulated by visual acuity constraints.

Intra-line Saccades

Most reading saccades are intra-line, as they begin and end within the same line of text. Intra-line saccades are usually about 7-8 characters long (Rayner, 1978; Yang & Vitu, 2007). These saccades are thought to target the centre of words- also known as the *optimal viewing position* (OVP)[1] (McConkie, Kerr, Reddix, & Zola, 1988; O'Regan, 1992; O'Regan & Levy-Schoen, 1987). The OVP is the fixation location that facilitates word recognition the most (Rayner, 2009). However, initial fixations usually land a little to the left of the word's centre (McConkie et al., 1988; Rayner, 1979; Vitu, O'Regan, & Mittau, 1990). This is known of as the *preferred viewing location* (PVL) effect (Rayner, 1979). The PVL may occur because readers aim for the OVP, but undershoot this location due to saccadic range error (McConkie et al., 1988). This saccade targeting mechanism has been implemented in most

[1] This location was originally called the "convenient viewing position" (O'Regan, 1981).

recent models of eye-movement control during reading (e.g., Engbert, Nuthmann, Richter, & Kliegl, 2005; Reichle, Warren, & McConnell, 2009; Snell, van Leipsig, Grainger, & Meeter, 2018).

Research has shown that saccade length in alphabetical languages is guided by the number of letters that the eyes travel rather than distance in visual angle (but see Shu, Zhou, Yan, & Kliegl, 2011; Yan, Zhou, Shu, & Kliegl, 2015 for potential differences in non-alphabetic scripts). For example, Morrison and Rayner (1981) changed the viewing distance of the text so that the width of each letter was 0.35º, 0.47º or 0.69º. They found that the amplitude of intra-line saccades remained the same in terms of the number of characters traversed. This finding was later replicated by O'Regan (1983) using a similar method. These results suggest that readers adjust the absolute size of their saccades in visual angle to match the size of letters in the text.

Studies that directly manipulated the font size of text have confirmed these results. For instance, Bullimore and Bailey (1995) found that the forward saccade length in letters remained relative constant with increasing font size when subjects with normal vision read a text chart. Similarly, Beymer, Russel, and Orton (2008) used a Verdana font that ranged from 10 to 14 pt. in size. They also found that saccade length in letters was not influenced by font size. Additionally, Miellet, O'Donnell, and Sereno (2009) reported that parafoveal magnification of the upcoming text did not influence saccade length in letters compared to reading without magnification, which also suggests that intra-line saccades are guided by character information. Saccade length has also been shown to scale with the amount of spacing used between letters and words even when the letters themselves remain the same size (Slattery & Rayner, 2013; Slattery, Yates, & Angele, 2016).

However, there is some evidence suggesting that saccade length in letters could be mildly influenced by font size. Franken, Podlesek, and Možina (2015) found that saccade length in letters decreased with increasing font size. In their study, letter sizes ranged from 0.21º to 0.46º and the biggest change in saccade length was observed for the smallest font sizes. Additionally, Yan et al. (2015, Experiment 2) manipulated the font size of German sentences where the letter width was 0.30°, 0.45°, or 0.60°. They also found that forward saccade length in letters decreased with increasing font size (the largest difference was about a character). These last two studies suggest that it may be an oversimplification to conclude that saccade length in letters is completely independent from font size. Nevertheless, all studies consistently show that there is a strong saccadic adaptation to font size where the absolute saccade length in visual angle becomes larger with bigger fonts in order to match the larger size of letters. This clearly suggests that intra-line saccades are guided by font size information.

Return-sweep Saccades

Return-sweeps move gaze from the end of one line of text to the beginning of the next. They travel much farther than intra-line saccades, typically some 30-70 characters. Return-sweeps are usually launched 4-6 characters from the end of the previous line (Hofmeister, Heller, & Radach, 1999; Parker, Slattery, & Kirkby, 2019) and land 5-8 characters from the beginning of the new line (Hofmeister, 1998; Parker, Slattery, et al., 2019; Slattery & Vasilev, 2019). One important factor that influences return-sweeps is line length. With longer lines, readers tend to land further to the right from the line start (Hofmeister et al., 1999). This rightward shift in landing positions likely results from increased saccadic error, as longer saccades are more likely to undershoot their target (Bartz, 1967; Henson, 1979).

Saccadic undershoot appears to be a basic aspect of the oculomotor system as long saccades are often followed by a shorter corrective saccade (Becker, 1972). For example, Becker and Fuchs (1969) noted that long saccades typically travel about 90% of the distance to the target and that a second, corrective saccade usually covers the remaining 10%. Most return-sweeps are long saccades and often fail to reach the beginning of the new line at once (Andriessen & de Voogd, 1973). Rather, readers generate a corrective saccade after approximately 40-60% of all return-sweeps (Hofmeister, 1998; Parker, Slattery, et al., 2019; Slattery & Vasilev, 2019). Corrective saccades are more likely to occur with long compared to short previous lines (Hofmeister et al., 1999). This is consistent with evidence showing that the probability of making a corrective saccade increases with greater target distance (Henson, 1979; Hyde, 1959; Weber & Daroff, 1971).

The fixation between a return-sweep and a corrective saccade has been called an *under-sweep fixation* by Parker, Kirkby, and Slattery (2017). These fixations are usually much shorter than the average reading fixation and last for approximately 120-160 ms (Hofmeister, 1998; Parker, Slattery, et al., 2019; Slattery & Parker, 2019; Slattery & Vasilev, 2019). Under-sweep fixations were originally thought to be unrelated to text processing and reflect the time needed to program a corrective saccade (e.g., Abrams & Zuber, 1972). However, recent evidence has suggested that readers may acquire useful information during such fixations that can later aid reading (Slattery & Parker, 2019). Additionally, reducing the oculomotor error associated with return-sweeps does not improve reading speed (Slattery & Vasilev, 2019), which further suggests that readers acquire useful information during under-sweeps.

While the basic characteristics of return-sweeps are well documented, less is known about what information is used to program such saccades. Intra-line saccades are thought to target words' OVP (McConkie et al., 1988), which is facilitated by the fact that the next word usually falls in parafoveal vision. However, return-sweeps are much longer, and their target usually falls well into peripheral vision where acuity is limited. To test whether return-sweeps target the OVP of words similar to intra-line saccades, Slattery and Vasilev (2019) examined how landing positions are influenced by the length of the first word on the line. They found that return-sweep landing positions were not influenced by line-initial word length, even when this word was formatted in bold to make it more prominent. Rather, readers appeared to target the left margin of the new line as landing positions shifted closer to the line start due to the bolding. This suggests that readers rely on different information for targeting return-sweeps than for targeting intra-line saccades.

As noted previously, intra-line saccades are guided by character information. However, there is surprisingly little evidence on how font size influences return-sweeps. To our knowledge, Hofmeister's (1998) Experiment 2 is the only study to address this question. In this experiment, eight participants read a text in four font size conditions that corresponded to letter widths of 0.27, 0.33, 0.39, and 0.44º. Hofmeister found that return-sweep landing positions in visual angle shifted further to the right of the line start with increasing font size. Because there are fewer characters to occupy the same physical area with larger fonts, this rightward shift suggests that return-sweeps may also be influenced by letter information. Additionally, corrective saccade frequency decreased with greater font size. However, the words at the beginnings and endings of lines were not controlled in Hofmeister (1998). This leaves open the possibility that lexical information around the launch and landing sites of return-sweeps was at least partially responsible for the reported effects.

Present Study

The present study manipulated text size to test whether return-sweep saccades are guided by character information in a similar way to intra-line saccades, and whether the use of character information depends on visual acuity constraints. This is important as return-sweeps differ from intra-line saccades in ways that could make character information a less reliable targeting cue. First, return-sweep targets usually fall well into peripheral vision and readers do not have the benefit of parafoveally previewing them (Parker, Nikolova, Slattery, Liversedge, & Kirkby, 2019; Parker, Slattery, et al., 2019). Second, readers appear to target an area relative to the left margin rather than the centre of the first word on the next line (Slattery & Vasilev, 2019). Therefore, one plausible saccade targeting strategy would be to ignore global text characteristics and instead focus only on locating the left text margin. This strategy predicts that font size would not influence return-sweep landing positions in visual angle as the left margin remains constant across different font sizes.

A second possibility is that return-sweeps are targeted to place gaze a number of characters to the right of the margin for optimal visual encoding. In this scenario, readers must use global text characteristics such as font size when programming return-sweeps. Therefore, consistent with Hofmeister's (1998) results, their landing positions in visual angle should shift to the right with larger fonts so that gaze would start at a similar character across different font sizes. This would be in line with O'Regan's (1990) "strategy-tactics" theory in which the eyes are guided by a general strategy of scanning the text based on its gross visual characteristics.

To examine the role of visual acuity, we manipulated the length of the line from which readers launch their return-sweeps. With longer lines, visual acuity of the saccade target will be reduced as the target will move further into peripheral vision. If return-sweeps are indeed guided by character information, landing positions may be more strongly influenced by font size with shorter lines as the targets will be closer to the fovea than with long lines. Therefore, if the use of character information depends on visual acuity, the font size effect in landing positions should become smaller with longer lines.

To test these questions, a 2 (font size: small [0.29º] vs. large [0.39º]) x 2 (line length: short [16º] vs. long [26º]) within-subject design was used. This manipulation ensures that, for a given line length, both font sizes will subtend the same visual angle but the larger font will have fewer characters than the smaller font. The line length conditions were chosen as to create a sizeable difference in visual acuity and the distance to the saccade target. The full preregistered (https://osf.io/9sngw) hypotheses are presented in Table 1. In addition, we explored whether readers gradually learn to adapt their return-sweep targeting decisions based on exposure to a certain font size. This was done by examining how trial order within each font size block influenced landing positions. We expected that when readers switch from the smaller to the larger font, they will gradually learn to shift their landing position further to the right as the letters will be larger and occupy a greater area. Conversely, we expected the opposite trend to occur for participants starting with the large font block and moving to the small font block.

Method

Participants

Sixty-four Bournemouth University students (52 female) participated for course credit. Their average age was 20.05 years (*SD*= 1.42 years; range 18-26 years). All participants were naïve as to the purpose of the experiment and were fluent English readers who reported normal or corrected-to-normal vision and no history of reading disorders. Sixty-one participants were native English speakers while three participants were fluent readers who had used the language for at least five years. The study was approved by the Bournemouth University Research Ethics Committee (ID 25619). Each participant provided informed written consent. The study protocol was pre-registered before data collection (https://osf.io/9sngw).

Table 1

An Outline of All Hypotheses in the Present Study

Number	Prediction
H1	Longer lines should result in return-sweep landing positions shifted further to the right due to the increase in saccadic range error.
H2	If return-sweeps are guided by visual angle alone, there should be no main effect of font size because participants will land at the same location (in visual angle relative to the left margin) regardless of font size (**H2.1**). If return-sweeps are at least partially guided by character information, then with the larger font the landing position should shift to the right relative to the smaller font (**H2.2**).
H3	If character information plays a role (see **H2.2**), the font size effect on landing positions should become smaller with an increase in line length (i.e., line length by font size interaction). This is because, with longer lines, letters at the start of the line will be located further into peripheral vision and therefore character information will be a less reliable cue for programming return-sweeps.
H4	Because intra-line saccades are targeted towards the words' OVP, the progressive saccade length in visual angle should become larger with increasing font size (Slattery & Rayner, 2013; Slattery et al., 2016). However, the length of return-sweep saccades should either be shorter when fonts are larger (see **H2.2**), or there should be no difference in return-sweep saccade lengths between the font size conditions (see **H2.1**). This should therefore result in an interaction between font size and saccade type (intra-line vs. return-sweep).
H5	Based on Hofmeister (1998), we predict that the frequency of corrective saccades will decrease in the bigger compared to the smaller font (**H5.1**). Additionally, we predict a main effect of line length, with greater frequency of corrective saccades for the long compared to the small line length (**H5.2**). This is because there is greater amount of saccadic range error with an increase in line length.
H6	If the reduction of corrective saccades with larger fonts (**H5.1**), as reported by Hofmeister (1998), is due to there being fewer characters to the left of fixation, there should be an interaction between line length and font size. This is because, at a given return-sweep landing site (in visual angle relative to the left margin), there will be more characters to the left with the small font than with the large font and this difference will grow larger the further to the right the return-sweep lands. With longer lines, landing sites will shift to the right, thereby yielding a larger font size effect.

Note: In the pre-registered protocol, hypothesis H5.2 was repeated by mistake within the text of Hypothesis H1. Therefore, we have removed the mention of this prediction from H1 and kept it in H5.2 for simplicity.

The sample size was calculated *a priori* based on a power analysis using the PANGEA software (Westfall, 2015). The expected effect sizes were calculated based on Hofmeister's (1998) Experiments 1-2. The analysis indicated that at an alpha level of 0.05, 64 participants were needed to achieve 80% power (Cohen, 1988) of detecting the smallest effect size (d= 0.325).

Materials and Designs

The stimuli consisted of 100 declarative sentences (see Figure 1). Each sentence appeared on two lines. The experiment had a 2 x 2 within-subject design with *font size* (small vs large) and *line length* (short vs long) as the factors. In the small font condition, the width of all characters was 12 pixels (0.295º). In the large font condition, the width of all characters was 16 pixels (0.394º). The first line of text was 16º in the short line condition and 26º in the long line condition. When constructing each item, a maximum deviance of ±0.5º was allowed in both line length conditions; as such, the average line length across all items was 15.97º for the short line condition and 26.02º for the long line condition.

The two independent variables were manipulated by changing the number of letters on the first line. Care was taken to ensure similar sentence meanings across the four conditions. The first and last four words on the first line were held constant across the four conditions. This ensured that readers processed the same words when they were about to make a return-sweep. The first line of text contained on average 54 characters in the small-font/ short-line condition (7 to 13 words; M= 10.12 words), 41 characters in the large-font/ short-line condition (6 to 10 words; M= 7.91 words), 88 characters in the small-font/ long-line condition (11 to 21 words; M= 15.71 words) and 66 characters in the large-font/ long-line condition (9 to 16 words; M= 12.26 words). The second line was identical in all experimental conditions and contained on average 50 characters (5 to 14 words; M= 8.67

words). The assignment of conditions to sentences was Latin-square counter-balanced across participants. The two font size conditions were blocked, and block order was counter-balanced across participants. The items within each block appeared in a pseudo-random order.

a) small-font/ short-line

The three musicians organised a tour last year to meet

their fans and celebrate the release of their new studio album.

b) large-font/ short-line

The two DJs did a tour last year to meet

their fans and celebrate the release of their new studio album.

c) small-font/ long-line

The three award-winning musicians decided to organise a national tour last year to meet

their fans and celebrate the release of their new studio album.

d) large-font/ long-line

The award-winning DJs organised a national tour last year to meet

their fans and celebrate the release of their new studio album.

*Figure 1***.** An example sentence used in the four experimental conditions. The line length manipulation occurred only on the first line.

Apparatus

Eye-movements were recorded with an SR Research EyeLink 1000 eye-tracker at 1000 Hz. Viewing was binocular, but only the right eye was recorded[2]. Participants' head was stabilised with a chin-and-forehead rest. The text was presented on a Cambridge Research

[2] The left eye was recorded for two participants due to tracking problems caused by wearing glasses or contact lenses.

Systems LCD++ monitor (resolution: 1920 x 1080 pixels; refresh rate: 120 Hz). The text was formatted in a monospaced Consolas font and appeared as left-aligned black letters over white background. The stimuli were centred vertically and appeared with a 200-pixel offset horizontally with double-spaced lines. The distance between participants' eye and the monitor was 80 cm. At this distance, each letter subtended 0.295º in the small font condition and 0.394º in the large font condition. The experiment was programmed in Matlab R2014a (MathWorks, 2014) using the Psychtoolbox v.3.0.11 (Brainard, 1997; Pelli, 1997) and Eyelink (Cornelissen, Peters, & Palmer, 2002) libraries. The experiment was run on a Windows 7 PC.

Procedure

A 9-point calibration was performed before the experiment. Calibration accuracy was monitored with a drift check before each trial. Participants were recalibrated whenever the error was > 0.4º. The experiment started with six practice trials (three in the small font and three in the large font condition). Each trial started with a black gaze-box centred at the first letter in the sentence. Once the gaze-box was fixated, it disappeared, and the sentence was presented on the screen.

Participants clicked the left button of the mouse to indicate they had finished reading the sentence. After 40% of trials, a True/ False comprehension question was presented, and participants used the mouse to select the correct answer. For example, in the sentence "The three musicians organised a tour last year to meet their fans and celebrate the release of their new studio album.", the question was "The artists celebrated the release of a new album. True/False?". The questions could be answered equally well in all conditions as they were based on information that was shared among them. The experiment lasted about 25-35 minutes and participants took a short break halfway through.

Data Analysis

Three measures were analysed: 1) landing position of return-sweeps in visual angle relative to the left margin; 2) the probability of making an under-sweep fixation; and 3) length of intra-line and return-sweep saccades. An *under-sweep* was defined as a return-sweep saccade that undershoots the line start and is followed by a corrective saccade to the left (Parker et al., 2017). The data were analysed with (Generalised) Linear Mixed Models ((G)LMMs) using the lme4 package v.1.1-21 (Bates, Machler, Bolker, & Walker, 2014) in the R software v.3.53 (R Core Team, 2019). Sum contrast coding was used for the font size (small font: -1; large font: 1) and line length factors (short line: -1; long line: 1). In the saccade length model, intra-line saccades were codes as -1 and return-sweep saccades were coded as 1. In the landing position and under-sweep probability models, launch site was added as a covariate.

Random intercepts were added for both participants and items (Baayen, Davidson, & Bates, 2008). As indicated in the pre-registration, we planned to add random slopes for font size and line length for both participants and items if the models converged (Barr, Levy, Scheepers, & Tily, 2013). If they did not, we planned to remove slopes until convergence was achieved. The landing position and under-sweep probability models converged only with a random slope of line length for participants and items. The saccade length model converged only with a random slope of font size for participants. The results were statistically significant if the $|t|$/ $|z|$ values were $\geq$2.

Modulation of landing positions by trial order was tested with Generalised Additive Mixed Models (GAMMs) (Baayen, Vasishth, Kliegl, & Bates, 2017; Sóskuthy, 2017; Wieling, 2018; Wood, 2017). GAMMs are an extension of GLMMs where part of the predictors are specified as smooths. These smooths represent the weighted sum of a number of base functions (Baayen et al., 2017). In this model, cubic regression splines were used as the base functions (Sóskuthy, 2017). The addition of smooths makes GAMMs well-suited to model temporally-correlated data, particularly if they exhibit a potentially non-linear relationship. Smooth terms were added for the effect of trial order within blocks, as well as for the by-subject and by-item random intercepts and random slopes. The GAMM models were fit with the “mgcv” v.1.8-26 R package (Wood, 2017) and visualised with the “itsadug” v.2.3 R package (van Rij, Wieling, Baayen, & van Rijn, 2017). The remaining graphs were generated with ggplot2 (Wickham, 2016).

Results

The mean comprehension accuracy was 97.9% (SD= 14.4%), indicating that participants understood the sentences. There were no significant differences in comprehension accuracy across the conditions (all $|z| \leq 0.94$). The data were pre-processed manually with EyeDoctor (Stracuzzi & Kinsey, 2009) to align the vertical position of fixations whenever necessary. During the pre-processing, 0.05% of trials were removed due to tracking loss. A further 0.03% were excluded as participants made no return-sweeps on that trial. Additionally, 4.44% of trials were discarded due to blinks occurring on return-sweeps or immediately before or after a return-sweep. Fixations shorter than 80 ms that occurred within 14 pixels (the mean of the two font size conditions) of a temporally adjacent fixation were merged. Any remaining fixations less than 80 ms were discarded[3]. Fixations longer than 1000 ms and their adjacent saccades were removed as outliers (0.03%). This left 95.45% of the data for analysis (6109 trials). Descriptive statistics are shown in Table 2.

[3] There were more fixations less than 80 ms for under-sweep (n= 40) compared to accurate-sweep cases (n= 4), $\chi^2(1)= 29.455$, $p= 5.7\text{x}10^{-8}$. However, keeping these fixations in the data did not change the main results or the conclusions from the analyses.

Table 2

Mean Descriptive Statistics of Saccade Measures in the Experiment (SDs in Parenthesis)

Line length	Font size	Landing position (deg)	Under-sweep probability	Saccade length (deg)	
				Intra-line	Return-sweep
Short	Small	1.05 (1.17)	0.51 (0.50)	2.53 (1.31)	12.5 (2.08)
Short	Large	1.38 (1.33)	0.44 (0.50)	3.07 (1.58)	11.7 (2.23)
Long	Small	1.99 (1.57)	0.79 (0.41)	2.71 (1.46)	22.3 (2.59)
Long	Large	2.34 (1.82)	0.71 (0.45)	3.28 (1.76)	21.5 (2.86)

Note: Landing position and saccade length are measured in degrees per visual angle.

Landing Position

The landing position results are illustrated in Figure 2a and the LMM analysis is shown in Table 3. Consistent with **H1**, participants landed further to the right in the long compared to the short line condition (*d*= 0.53). Additionally, consistent with **H2.2**, landing positions shifted further to the right in the large compared to the small font condition (*d*= 0.21). This indicates that character size information is used when programming return-sweeps. The launch site effect was also significant, indicating that return-sweeps that were launched further away from the end of the first line landed closer to the left margin. Critically, however, there was no two-way interaction between font size and line length. Therefore, contrary to **H3,** the use of character information for saccade targeting did not depend on the visual acuity of the target.

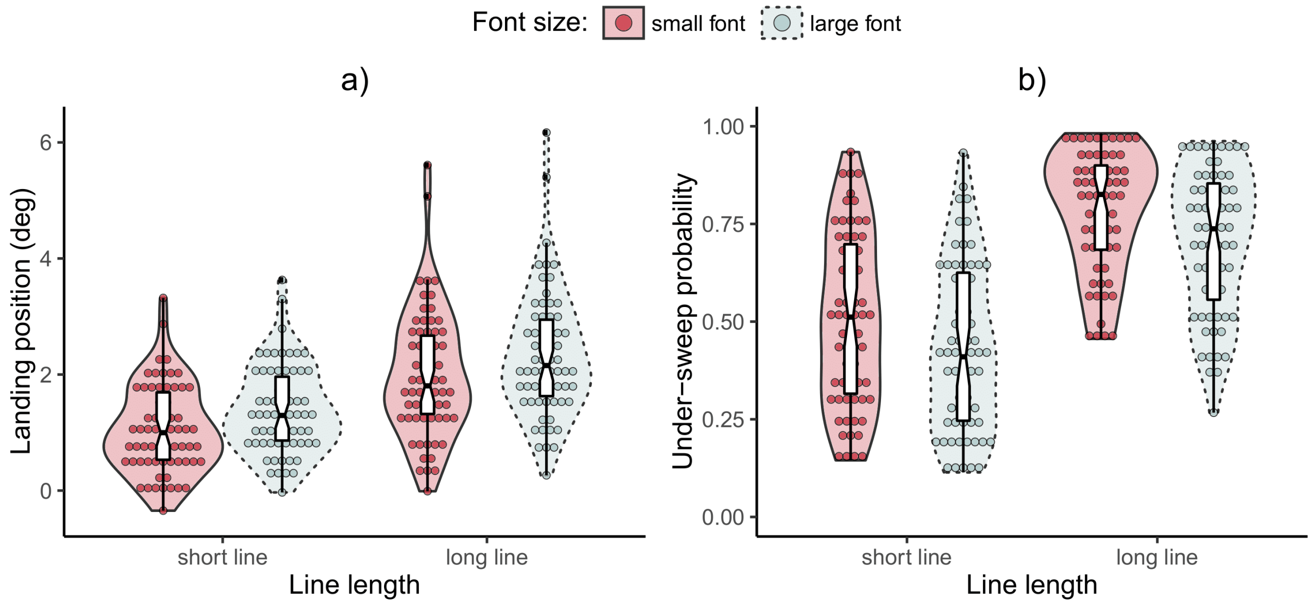

Figure 2. Box plots and probability densities for the landing position (**a**) and under-sweep probability (**b**) measures. Dots represent the mean value for each subject, as estimated by the (G)LMM model. The central mark on each boxplot shows the median.

Furthermore, there was a significant two-way interaction between font size and launch site. The main effect of launch site was less pronounced in the large compared to the small font condition. Therefore, launch site exerted less of an influence on landing positions when there were fewer, but bigger, characters on the line. Interestingly, the three-way interaction between font size, line length and launch site also reached significance. As Figure 3 illustrates, in the small font condition, launch sites that were closer to the left margin resulted in return-sweeps that landed closer to the left margin for both line length conditions. However, in the large font condition, the launch site effect went in the opposite direction for the two line length conditions. While the same effect was observed for short lines, the trend went in the opposite direction for long lines. That is, launch positions that were closer to the left margin paradoxically led to landing positions further away from that margin. Therefore, the launch site effect was less pronounced in the large font sentences because the two line length conditions were largely cancelling each other out.

Table 3

(G)LMM *Results for Landing Position in Degrees per Visual Angle and Under-sweep Probability as a Function of Font Size, Line Length, and Launch Site*

Fixed effects	Landing position (deg)			Under-sweep probability		
	b	SE	t	b	SE	z
Intercept	1.685	0.117	**14.354**	0.643	0.149	**4.329**
Font size	0.179	0.015	**12.157**	-0.189	0.032	**-5.934**
Line length	0.464	0.033	**13.943**	0.751	0.057	**13.211**
Launch site	-0.05	0.016	**-3.151**	-0.295	0.036	**-8.111**
Font size x Line length	0.01	0.015	0.655	-0.042	0.032	-1.327
Font size x Launch site	0.032	0.015	**2.144**	0.013	0.034	0.396
Line length x Launch site	0.006	0.016	0.377	< 0.01	0.035	-0.007
Font size x Line length x Launch site	0.046	0.015	**3.02**	0.011	0.034	0.316
Random effects	Var.	SD	Corr.	Var.	SD	Corr.
Intercept (items)	0.039	0.197	-	0.171	0.413	-
Intercept (subjects)	0.842	0.917	-	1.220	1.104	-
Line length slope (items)	0.006	0.080	0.93	0.026	0.162	0.22
Line length slope (subjects)	0.052	0.229	0.73	0.107	0.327	0.11
Residual	1.276	1.129	-	-	-	-

Note: statistically significant t-/ z-values are formatted in bold. Launch site was centred at 0.

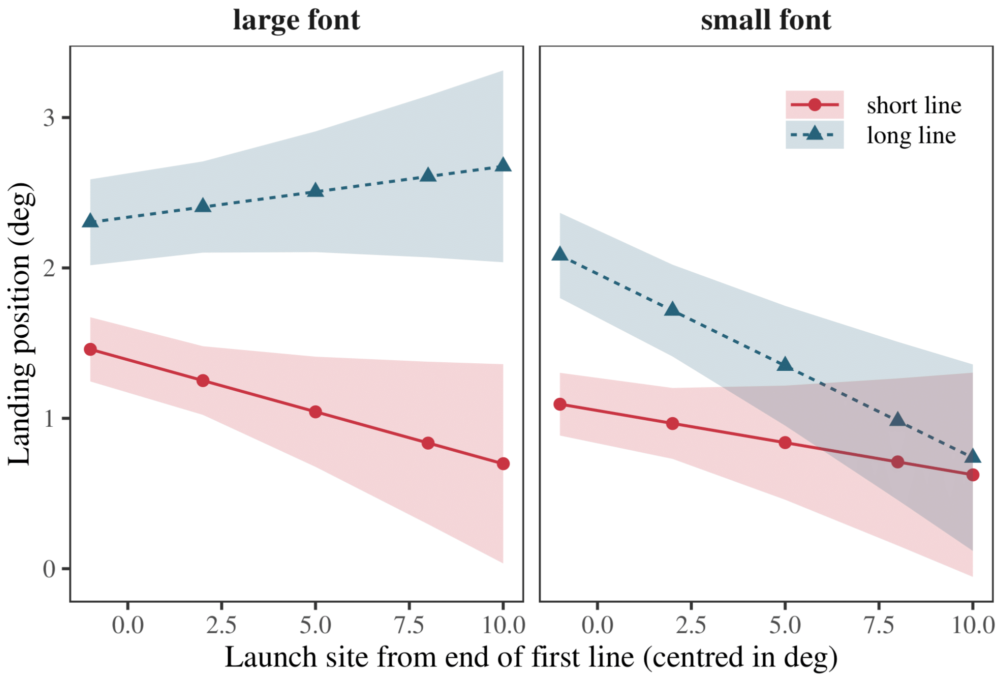

Figure 3. Three-way interaction between font size, line length and launch site in the landing position model. Greater launch site numbers indicate greater distance from the end of the first line and therefore correspond to a shorter distance to the beginning of the next line. Shading indicates ±1 SE. The fitted values from the model were extracted with the "effects" R package v.4.1 (Fox & Hong, 2009).

Modulation of Landing Position by Trial Order

One question of interest was how trial order within the font size blocks may influence participants' landing positions. If landing positions are modulated by trial order, this would suggest that participants gradually learn to adjust their targeting decisions based on increased exposure to a given font size. A GAMM model was fit for each of the two font size conditions. The results are visualised in Figure 4. In the large font condition, there was a main effect of block order (b= 0.161, SE= 0.059, t= 2.715), indicating that return-sweeps landed further to the right when large font sentences were presented in the first block. Because there are more characters occupying the same physical area in the small font condition, participants tend to land closer to the left margin (see above). Therefore, when the large font sentences are presented as the second block following the small font ones, readers are still accustomed to targeting for the smaller font, thus leading to this main effect. Interestingly, with increasing trial order within the large font block, there was a tendency for landing positions to shift further to the right. This indicates that there was at least some adaptation to the larger font size within the block (see Figure 4a). However, neither the effect of trial order nor its interactions with block order reached significance (all *p*s ≥ 0.16).

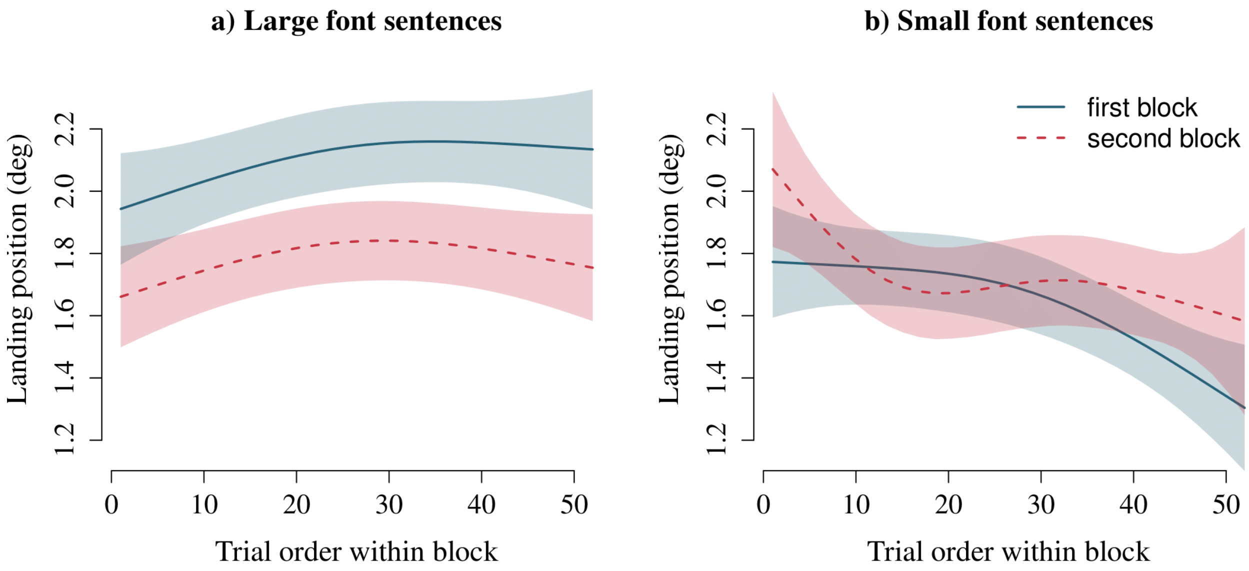

Figure 4. Modulation of return-sweep landing positions by trial order and block order in the experiment. Plotted are the estimated slope smooths from the GAMM model for the large font (**a**) and small font (**b**) conditions. Each font size condition was presented either as the first or the second experimental block (counterbalanced). Shading indicates the 95% confidence interval.

In contrast, with the small font sentences, there was no main effect of block order (t= 1.197), which indicates that landing positions were not influenced by whether the small font block was presented first or second. However, the smooth term of trial order was significant (edf= 1.715, $F(2.131)$= 6.005, p= 0.002). This was due to return-sweeps landing closer to the left text margin with increasing number of sentences that participants read. This indicates that participants continued adapting their landing positions to the smaller text font throughout the block. The adaptation was slightly stronger when the small-font sentences were presented in the second block, although this trend did not reach significance (*edf*= 2.915, $F(3.621)= 2.298$, $p= 0.086$). In summary, there was at least some evidence to suggest that landing positions can be modulated by increased exposure to the same font size.

Saccade Length

Saccade length in visual angle was analysed by comparing return-sweeps to forward intra-line saccades in the two font size conditions. For completeness, line length was included as a predictor. However, the interaction between font size and saccade type (intra-line vs. return-sweep) is of main theoretical importance[4]. The results are presented in Table 4. There was a main effect of saccade type, which indicated that return-sweeps travelled farther in visual angle compared to intra-line saccades. Additionally, saccades were significantly longer when the first line of text was also longer. This effect was largely due to the increase in saccade length for return-sweeps with longer lines, which is shown by the robust line length by saccade type interaction. Crucially, consistent with **H4**, there was a significant interaction between font size and saccade type. This occurred because forward intra-line saccade lengths increased as the font size increased but return-sweep saccade lengths decreased as font size increased. In both cases, this change reflects saccadic adaptation to the font size of the text.

[4] The pre-registration also included launch site as a covariate. However, as this is not of main theoretical interest, the covariate was not included.

Table 4

LMM Results for Saccade Length in Visual Angle as a Function of Font Size, Line Length and Saccade Type (Return-sweep vs Intra-line)

Fixed Effects	b	SE	t
Intercept	7.496	0.051	**145.9**
Font size	-0.06	0.019	**-3.17**
Line length	4.983	0.022	**227.1**
Saccade type	4.635	0.016	**292.6**
Font size x Line length	-0.004	0.022	-0.179
Font size x Saccade type	-0.338	0.016	**-21.33**
Line length x Saccade type	4.792	0.022	**218.4**
Font size x Line length x Saccade type	-0.012	0.022	-0.553
Random Effects	**Var.**	**SD**	**Corr.**
Intercept (items)	0.016	0.129	-
Intercept (subjects)	0.141	0.376	-
Font size slope (subjects)	0.006	0.082	0.43
Residual	2.480	1.575	-

Note: statistically significant *t*-values are formatted in bold.

Under-sweep Probability

The under-sweep probability results are illustrated in Figure 2b and the GLMM model results are presented in Table 3. Consistent with **H5.1**, the frequency of corrective saccades decreased in the large compared to the small font condition (*d*= -0.15). This indicates that readers were less likely to make a corrective saccade in the large font condition. Additionally, consistent with **H5.2**, under-sweep probability increased in the long line compared to the short line condition (*d*= 0.59). This suggests that there was greater oculomotor error associated with longer lines, which led to an increase in corrective saccades. There was also a main effect of launch site, which was due to greater probability of making an under-sweep fixation when the launch site was further from the left margin to begin with. Finally, contrary to **H6**, the interaction between font size and line length was not significant—the font size effect was not modulated by the length of the previous line.

Discussion

We examined whether return-sweep saccades are guided by character information and whether visual acuity constraints modulate the use of such information. The key findings can be summarised as follows. First, consistent with Hofmeister (1998), the larger font led to return-sweeps landing further to the right of the line start and a smaller probability of making an under-sweep fixation compared to the smaller font. This clearly suggests that character information is used in return-sweep and corrective saccade planning. Second, when return-sweeps were launched from a longer line, landing positions also shifted to the right and the probability of making an under-sweep fixation increased. This likely reflects the increase in saccadic error, also replicating previous results (Hofmeister et al., 1999). Third, visual acuity at the saccade target did not modulate the use of character information, as indicated by the lack of a font size by line length interaction. This suggests that the use of font size information does not depend on how far into the periphery the saccade target is, at least up to 26º. Finally, there was some evidence to suggest that readers dynamically modulate their landing positions with increased exposure to a given font size, although this was mostly evident in the smaller font block. We hypothesise that with the smaller font block, landing sites which were too far to the right would be less optimal and likely require a corrective saccade in order to process the smaller characters to the left of fixation. However, with the larger font, there may be less pressure for readers to adjust their targeting strategy because there will be fewer and larger letters to the left.

While return-sweeps traverse a much larger distance than intra-line saccades, the present data clearly suggest that these longer saccades are also guided by font size information. Therefore, the present results do not support a saccade targeting strategy in which readers always aim for the same physical location on the next line while ignoring letter size information. Rather, readers take into account the formatting of the text and aim for a location on the next line that allows for efficient processing of letters based on their size. Additionally, the use of character information did not depend on visual acuity at the saccade target as the font size effect on landing positions was not modulated by the length of the previous line. This suggests that font size information is used as a global targeting cue because it does not depend on how well readers can perceive words at the beginning of the next line. This is consistent with O'Regan's (1990) account in which saccade size does not depend on visual acuity constraints but is instead influenced by gross visual characteristics of the text such as font size. Interestingly, return-sweeps are also influenced by letter spacing in a similar way to font size- when the spacing between letters increases, landing positions also shift to the right (Hofmeister, 1998, Experiment 3). Therefore, even though visual acuity at the line start is usually limited, readers use global text formatting information to help them land in a more optimal viewing position.

The preference to land in a position optimized for the size of letters is interesting when one considers the fact that return-sweeps do not appear to target the OVP of the line-initial word (see Slattery & Vasilev, 2019). Because return-sweeps are typically launched at least 10º away from the target, accurately aiming for the first word's OVP may not be a feasible strategy. Rather, by aiming for a location relative to the left margin, readers may attempt to land in a position that leaves a few characters to the left of fixation. Consequently, the landing position in visual angle would be a function of font size—with larger fonts, this position would shift to the right to compensate for the bigger letters. This may be advantageous as the few characters to the left of fixation will usually fall within foveal vision and readers may be able to process line-initial information more optimally than if they had landed at the left margin itself. Additionally, landing a few characters from the line start may minimize the probability of overshooting the line start, which could reduce the overall flight time (Harris, 1995) or energy expenditure (Becker, 1989) of such eye-movements. Therefore, it may be more optimal to attempt to land a few characters from the line start.

Indeed, our analysis of trial order effects adds some strength to this explanation. Within a block, readers appear to gradually adjust the target location of their return-sweeps so that they land around the 5th character on the line in both the small and large font size conditions. However, this gradual shift was only statistically significant in the small font block. As already mentioned, this may be due to a larger cost of landing too far from the line start when the characters on the line are smaller. Across the large font block, there was a main effect of block order rather than trial order as readers who saw the small font stimuli first began the large block stimuli with landing positions closer to the margin, as one would expect if they had become accustomed to the smaller font. However, this also may be due to our participants being more accustomed to reading text closer in size to that of our large font condition.

There was one unexpected effect in the landing position analysis. We found evidence of a three-way interaction between font size, line length, and launch site which also drove a two-way interaction between font size and launch site. With the small font, landing positions shifted closer to the start of the new line as launch positions were further from the end of the prior line and this effect was more pronounced for the long line condition. However, for the large font, the effect of launch position was similar to the small font with the short lines but went in the opposite direction for the long lines (see Figure 3). This isn't the first time that launch site has been involved with an unpredicted interaction in an analysis of return-sweep landing position data. Recently, Slattery and Vasilev (2019) reported that launch site interacted with the length of line-initial words in predicting landing positions. Clearly, more research is needed to understand how launch sites influence return-sweep targeting.

One interesting finding from the undersweep-probability data was that corrective saccades were less likely when the font size was larger, presumably because there was less character information to the left of fixation to process. This result suggests that corrective saccades are not programmed solely as a function of the distance in visual angle between the landing position and the left margin. Clearly, the present data indicate that readers use character information at least to some degree to decide whether a correction is needed. However, it is important to note that the likelihood of a corrective saccade is not strongly based on character information. This was because there was no interaction between font size and line length in the under-sweep probability data. Because return-sweeps launched from a longer line will undershoot the line start to a greater extent compared to those launched from a short line, the difference in the number of characters to the left of fixation between the two font size conditions will increase with line length (see **H6**). Therefore, if the probability of making a corrective saccade is based only on character information, then we should have found an interaction between these two variables.

While the effect of font size was found in both landing positions and under-sweep probability, it is not clear whether its origin is the same. Because return-sweeps are programmed at the end of the previous line, the landing position effect must originate prior to the execution of the return-sweep. However, the corrective saccade is executed after readers have already landed on the next line, which means that they will have a higher resolution view of the line start. Therefore, it is not known whether the influence of font size on corrective saccades is based on visual feedback once readers have landed on the next line or whether it originates prior to the return-sweep saccade.

There has been a discussion in the literature about whether corrective saccades are pre-programmed before the main saccade (Barnes & Gresty, 1973; Becker, 1972, 1976; Becker & Fuchs, 1969; Shebilske, 1976) or whether they are based on visual feedback following the main saccade (Prablanc & Jeannerod, 1975; Prablanc, Massé, & Echallier, 1978). Because corrective saccades can occur even in the dark without any visual feedback (e.g., Barnes & Gresty, 1973; Becker & Fuchs, 1969), it has been suggested that they may come "pre-packaged" with the main saccade to save time (Becker & Fuchs, 1969). However, there is also some evidence showing that corrective saccades do not occur in the absence of visual feedback (Prablanc & Jeannerod, 1975). While this discrepancy could be partly due to methodological differences (Becker, 1976), it is important to note that the two viewpoints are not mutually exclusive. For example, recent evidence has suggested that, when the main saccade undershoots the target by more than 10%, a corrective saccade is likely to occur regardless of whether visual feedback was present or not (Tian, Ying, & Zee, 2013). Therefore, visual feedback may play a stronger role when the undershoot error is smaller.

Currently, little is known about how readers program corrective saccades following a return-sweep. Therefore, it is not clear whether the font size effect in under-sweep probability arises from visual feedback on the next line or whether it is "pre-packaged" with the main saccade based on the general expectation of larger letters in the text. Nevertheless, regardless of when this influence occurs, the present data indicate that readers use global text characteristics such as font size to determine if a correction is needed. In summary, the present study suggests that font size information is used as a global saccade targeting cue to help readers land in a more optimal viewing position at the start of the new line.

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Declaration of Conflicting Interests

The Authors declare that there is no conflict of interest.

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