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What is the optimal position of low-frequency words across line boundaries? An eye movement investigation

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Abstract

When displaying text on a page or a screen, only a finite number of characters can be presented on a single line. If the text exceeds that finite value, then text wrapping occurs. Often this process results in longer, more difficult to process words being positioned at the start of a line. We conducted an eye movement study to examine how this artefact of text wrapping affects passage reading. This allowed us to answer the question: *should word difficulty be used when determining line breaks?* Thirty-nine participants read 20 passages where low-frequency target words were either line-initial or line-final. There was no statistically reliable effect of our manipulation on passage reading time or comprehension despite several effects at a local level. Regarding our primary research question, the evidence suggests that word difficulty may not need to be accounted for when determining line breaks and assigning words to new lines.

It is often assumed that a reader's eyes move continuously along a line of text. However, it is clear from eye movement investigations that readers actually make a series of short, rapid *saccadic* eye movements which are separated by brief pauses, called *fixations*. A considerable number of experiments have investigated how various lexical variables influence eye movements during reading (for reviews see Rayner, 1998, 2009). The evidence clearly indicates that eye movements during reading are under direct cognitive control as fixation durations are largely determined by lexical properties of the fixated word, such as its frequency of occurrence in natural language (Dambacher et al., 2013; Inhoff & Rayner, 1986; Kliegl et al., 2004; Slattery et al., 2007) and its predictability from the preceding sentence context (Ehrlich & Rayner, 1981; Kliegl et al., 2004; Rayner et al., 2011; Rayner & Well, 1996). It is also apparent from the eye movement literature that readers obtain useful information from the word to the right of fixation (i.e. those appearing in the parafoveal region extending 2–5° of visual angle either side of fixation). Studies using the boundary change paradigm (Rayner, 1975) have continually shown that when a word in the parafovea is masked, and readers are denied valid preview, subsequent reading times on that word are longer (see Schotter et al., 2012, for discussion). While a great deal is known about how lexical variables and access to parafoveal information influence reading, comparatively few studies have employed eye movement technology to examine how components of text layout influence reading. In an attempt to address this shortcoming, we examined the optimal position for low-frequency words at line boundaries and addressed the question *should word difficulty be used when determining line breaks?*

Regarding text layout, studies of eye movements during reading have examined several areas (e.g. font, line length, spacing, and text justification; see Slattery, 2016, for a review). Of relevance to the current study are spacing and line boundaries. To date, the published literature has largely been concerned with the effects of spacing at the letter- and word-level. Evidence indicates that spacing between letters facilitates letter identification (Bouma, 1970; Chung et al., 2001; Eriksen & Eriksen, 1974; Marzouki & Grainger, 2014). At the word-level the picture is a little more complex; increases to intra-word spacing (i.e. the spacing between letters within a word) result in more rapid word identification up until a certain point (Perea & Gomez, 2012) where additional space inhibits the speed of word identification (Paterson & Jordan, 2010; Pelli et al., 2007; Risko et al., 2011; Vinckier et al., 2011). In a comparison of various fonts under several spacing manipulations, Slattery et al. (2016) indicated the optimal intra-word spacing for isolated word recognition was 30% of the average letter width. Of course, studies of isolated word recognition tell us little about how spacing influences reading behaviour as reading, unlike word identification paradigms, requires careful coordination of the oculomotor system.

It is clear from several studies involving alphabetic languages that reading becomes more difficult when inter-word spaces are removed (Perea & Acha, 2009; Pollatsek & Rayner, 1982; Rayner et al., 2014; Sheridan et al., 2013, 2016). Thus, inter-word spacing has important implications for reading sentences. Two studies that have investigated joint effects of intra-word and inter-word spacing indicate that inter-word spacing is likely more important to reading than intra-word spacing. First, Slattery and Rayner (2013) had participants read sentences where intra-word spacing was reduced and added to the end of the word thereby increasing inter-word spacing. These effects were presented in a fixed width font (Consolas) and a proportional font (Georgia). They reported that adjusted spacing led to shorter gaze durations on target words. However, this benefit was limited to the fixed width font which had a wider default intra-word spacing. The second study independently manipulated inter-word and intra-word spacing in a factorial design. Consistent with Slattery and Rayner (2013), Slattery et al. (2016) reported that spacing effects differed between fixed-width and proportional fonts. Increased reading difficulty associated with larger intra-word and smaller inter-word spacing both tended to be greater for proportional fonts.

The decision of how inter-letter and inter-word spacing should be implemented will not only affect the position of words within a line, but it will also affect how words are positioned across line boundaries. Line breaking, or word/text wrapping, refers to the process of breaking sections of text into lines so that it will fit the width of the page, screen, or other display area. The first step in line breaking is to determine the width of individual characters, taking kerning, ligatures, and spacing into account. The total number of characters to be placed on a line will be determined by taking the width of a line divided by the average width of individual characters (Slattery & Rayner, 2013). The next step is determining possible break points (typically white spaces in Latin writing systems). If the total number of characters on a line falls into a region of white space, then determining the line break is straightforward. But what happens when the maximum number of characters intersects a word? There exist several different algorithms that determine where in the text line breaks will occur in such situations based on what is being optimised.

One approach is to minimise raggedness, that is, to minimise the amount of blank space at the end of the line to produce an aesthetically pleasing result. Under this approach, space may be more evenly distributed between characters and words across the line to make characters fit. The second approach is to insert a soft hyphen such that a given word spans the line boundary (Bouckaert, 2003). When fitting text to a specific line-width, Microsoft Word uses syllable boundaries to determine automatic hyphenation. Of course, not all words are suited to this style of word wrapping (e.g. longer single syllable words such as 'thoughts'). An alternate approach would be to position a word at the start of a new line when it intersects a line break. Based on probability, longer words are more likely to intersect line boundaries and be positioned at the very start of the line. Indeed, Parker and Slattery (2019) reported that line-initial words in the Provo Corpus (Luke & Christianson, 2018) were longer on average (6.9 characters) than words at other line positions in the corpus (4.8 characters). On average, these words also had a lower frequency of occurrence, which is known to be related to the ease of word processing (e.g. Inhoff & Rayner, 1986). This is not surprising given the moderate to strong correlations reported in corpus-based analyses between word length and frequency (Kliegl et al., 2004; Parker & Slattery, 2019). This means that current approaches to text wrapping may result in words that are more difficult to process being positioned at the very start of the line. At the first glance, this may not seem like an issue; however, a growing body of evidence examining return-sweep saccades converges on the view that reading is less efficient at the very start of the line. This reduced processing efficiency combined with increased word difficulty may lead to longer reading times; hence our choice to examine the optimal positioning of long, low-frequency words. For the remainder of the Introduction, we summarise the return-sweep literature and consider the implications that positioning low-frequency words at the start of the line may have on reading.

The eye movement that takes a reader's fixation from the end of one line to the start of the next is referred to as a *return-sweep*. The fixations that precede return-sweeps are *line-final fixations*; which typically occur in a position relatively close to the end of a line (5–7 characters; Parker, Nikolova, et al., 2019; Parker, Slattery et al., 2019; Slattery & Vasilev, 2019). Return-sweeps follow two distinct trajectories. *Accurate return-sweeps* are those that land in a position that is close enough to their intended target that readers can begin a rightwards reading pass through the new line. *Under-sweeps* are those that land short of their target and require an immediate leftwards saccade towards the left margin prior to the rightwards reading pass. What differentiates the trajectory of these fixations is the direction of the saccade following the return-sweep. The trajectory of a return-sweep is heavily influenced by typographical factors such as line width, where under-sweeps are more frequent when lines are long (Parker, Nikolova, et al., 2019; Parker & Slattery, 2021; Vasilev et al., 2021), and line spacing, where vertical errors are less prevalent as line spacing increases and line length decreases (Tinker, 1963). As under-sweeps have classically been viewed as uninvolved in lexical processing, most of the typographical research on return-sweeps has focused on determining the optimal line width for reading which minimises the presence of under-sweep fixations (see Dyson, 2004, for a review). More recently, however, empirical work has investigated the influence of line boundaries and return-sweep execution on lexical processing. Below we provide detail on these return-sweep fixations in the order in which they occur during reading.

Line-final fixations are those that precede return-sweeps. Evidence indicates that line-final are shorter than intra-line fixations that are non-adjacent to return-sweeps (Parker, Nikolova, et al., 2019; Parker, Slattery, et al., 2019). Kuperman et al. (2010) argued that shorter fixation durations towards the end of the line could stem from the processing of line boundaries, whereby readers engage less in lexical processing to plan the return-sweep. Consistent with this, Hofmeister

(1997) reported a 20 ms increase in fixation duration for all reading fixations except for line-final fixations, suggesting that line-final fixations are relatively uninvolved in linguistic processing.

Accurate line-initial fixations are those resulting from an accurate return-sweep. Accurate line-initial fixations are longer in duration than those occurring within a line (Parker et al., 2020; Parker, Nikolova, et al., 2019; Parker, Slattery, et al., 2019; Parker & Slattery, 2019; Slattery & Vasilev, 2019). Furthermore, Parker et al. (2017) reported that words presented at the very start of the line receive longer reading times compared to the same words occurring within a line. It has been argued that longer reading times for words at the start of the line result from a lack of parafoveal preview (Parker, Nikolova, et al., 2019), that is the inability to process words prior to direct fixation such that lexical processing must be conducted under foveal viewing. Despite a lack of parafoveal preview for words at the start of the line, two studies have shown that lexical variables associated with word processing ease influence reading times on line-initial words. First, Parker et al. (2017) reported predictability effects for line-initial words which were numerically larger than those observed midline. This indicates that readers may rely on context to offset the unavailability of parafoveal preview. Second, Parker and Slattery (2019) reported effects of both frequency and predictability for line-initial words. In an analysis of the Provo Corpus, but not in a novel eye movement experiment, Parker and Slattery reported that frequency effects were larger for words at the start of the line indicating that low-frequency words may be more costly when presented in a line-initial position.

Under-sweep fixations are those which follow return-sweeps that require an additional corrective saccade towards the left margin prior to a rightwards reading pass. While their duration is not related to the lexical qualities of the word they land on (Slattery & Parker, 2019), the word they are targeted to (Parker et al., 2020), or reading skill (Parker & Slattery, 2021), readers are able to extract useful information during these fixations and access parafoveal information from the adjacent word to the left but not the right of fixation (Parker et al., 2020).

As each population of reading fixation are differentially involved in lexical processing, we see several ways in which the position of low-frequency words across line boundaries could influence reading. When readers fixate words at the very start of a new line, a lack of parafoveal preview demands that lexical processing must be carried out during the line-initial fixations. This results in longer line-initial fixations. If, as observed in Parker and Slattery's (2019) analysis of the Provo Corpus, lexical effects are stronger at the start of the line, positioning long, low-frequency words at the very start of the line may result in longer reading times when moving between lines. Over multiple lines of text, this has the potential to result in slower passage reading. Placing these long, low-frequency words in a line-final position, however, may not incur such a cost as readers will be able to engage in parafoveal processing prior to direct fixation. Furthermore, if, as argued by Hofmeister (1997), readers are engaging less in lexical processing during line-final fixations then they may also be less impacted by word frequency which may in turn promote quicker passage reading time. Of course, this may have a knock-on effect for reading comprehension. We explored these possibilities in a single eye movement study where low-frequency words were placed either at the very end or very start of a line. From an applied perspective, this would enable us to address the question: *should word difficulty be used when determining line breaks?*

1 | METHOD

1.1 | Participants

Forty-five adult participants were recruited from the Bournemouth University Community and provided written informed consent. They had spoken English for a minimum of 10 years, were naïve to the purpose of the study and had normal or corrected-to-normal vision. Six participants were excluded from the study. Two were excluded because their level of English did not meet the criteria, and four were excluded because of problems in eye-tracking (calibration or track loss). Data are reported for the remaining 39 participants (23 females and 16 males), aged 18 to 52 years old ($M = 23.0$, $SD = 6.02$). Participants read binocularly but only movements of the right eye were recorded – except for three participants whose left eye was recorded due to problems in calibrating the right eye.

1.2 | Materials

Twenty passages of text and two practice passages were written for the purpose of the study (see Appendix). Each passage had five or six lines with four target words embedded. Each passage contained 32–48 words ($M = 40.25$). Target words varied from 4 to 14 letters ($M = 8.69$) and had an average Zipf frequency (van Heuven et al., 2014), based on the SUBTLEX database (Brysbaert & New, 2009), of 2.54. The remaining words in a passage had an average length of 3.96 letters and an average zipf frequency of 5.04.

Each passage was shown in one of two conditions. In condition one, the low-frequency target words were the last words on the lines. In condition two, the low-frequency target words were the first words on the lines. The passages were identical in both conditions except for one word on the first line of text which was either a short version of a word (e.g. Em) in order to place the low-frequency target words at the ends of the lines or a longer version of the word (e.g. Emily) in order to place the low-frequency target word at the beginnings of the lines. An example passage is presented in Figure 1.

1.3 | Design

The study contained two within-participants conditions, where target words were line-final or line-initial. Two versions of the study were created with the 20 experimental items being assigned to the two conditions using a Latin-square design. Each version contained an equal number of items in each condition, no item appeared more than once in either version, and each item appeared in the opposite condition in the different versions.

```
Em was at the shopping centre looking for a **dustpan**
for her aunt who had recently moved into a **prefab**
in Bournemouth. The house included a large **scullery**
which her aunt would equip with hydrogen **peroxide**
and other cleaning products.

Emily was at the shopping centre looking for a
**dustpan** for her aunt who had recently moved into a
**prefab** in Bournemouth. The house included a large
**scullery** which her aunt would equip with hydrogen
**peroxide** and other cleaning products.
```

FIGURE 1 Example stimuli with low-frequency words (shown in bolded text) positioned at the start and the end of the line.

TABLE 1 Power estimates for a range of effect sizes.

Effect size (ms)	Estimated power
50	0.10 [0.04, 0.16]
150	0.14 [0.07, 0.21]
250	0.38 [0.28, 0.48]
350	0.69 [0.60, 0.78]
450	0.88 [0.82, 0.94]
550	1.00 [1.00, 1.00]
650	0.98 [0.95, 1.00]
750	1.00 [1.00, 1.00]
850	1.00 [1.00, 1.00]
950	1.00 [1.00, 1.00]

Note: Power estimates are shown as a proportion.

1.4 | Statistical power

The study was designed to address our research question in an exploratory manner as we did not have strong a priori predictions about the nature or direction of the effects. Instead, our final pragmatic sample size was determined by economic constraints. Given that we did not power our study to detect a minimum effect size of interest, there is a possibility that we may have lacked statistical power to observe small effects. We, therefore, include power simulations for our analysis of total passage reading time and report the theoretical power for a range of effect sizes.

Power simulations were modelled on DeBruine and Barr (2021, Appendix 2), who provided scripts for power analysis of linear mixed-effects models. Within these simulations, we simulated a data set with a single within-participant variable where each of the 39 statistical subjects contributed data to both conditions via a Latin square design. The size of the effect ranged from 50 to 950 ms in total passage reading time (for full details see https://osf.io/76huf/). Each of the effect sizes were simulated 1000 times. The results of these simulations, which tested the model $lmer(dv \sim condition + (1 \mid participant) + (1|item))$ are shown in Table 1. As can be seen, the current sample should provide sufficient power to detect a 450 ms effect of our manipulation in total passage reading time with at 88% power at an alpha level of $|t| > 1.96$. That is, it returned a significant effect of condition for 88% of the 1000 simulations. Accordingly, there was less theoretical power to detect smaller effects. Of course, detecting a small 50 ms effect in total passage reading time would have little theoretical and practical importance as the effect is so small relative to overall passage reading time which averaged 13,063 ms in the current study. Regardless, this has important consequences for the conclusions we make from the data.

1.5 | Apparatus

An SR Research EyeLink 1000 desktop-mounted system with a sampling rate of 1000 Hz was used to track eye movements. Stimuli were presented on a Cambridge Research Systems 32' Display++ LCD monitor with 1920 × 1080 resolution and with a viewing distance of 80 cm. Each character was presented in black 20-point Consolas font. Responses to comprehension questions were recorded via a VPixx five-button response box.

1.6 | Procedure

Participants were tested in a laboratory room at Bournemouth University. The procedure was approved by Bournemouth University's Research Ethics Committee (ID: 17533) in accordance with the Declaration of Helsinki. The participants were first asked to read an information sheet and give written informed consent. Demographic data were then recorded. Participants were informed that they would be reading passages for comprehension and answering a comprehension question after each passage (see Appendix). The comprehension question for the example stimuli shown in Figure 1 was:

Q: The scullery would be used to

1. store sporting equipment
2. store clothes
3. store cleaning supplies

Participants were instructed to press any button on the response box when they had finished reading the passage. They were then instructed to answer the multiple-choice questions by pressing the colour on the response button box that responded with the colour of the answer choice they thought was correct. Before starting the study, participants completed a 9-point calibration and validation procedure. The average error of the calibration and validation procedure had to be below 0.40 or the procedure was repeated. For the passages to appear on the screen participants first had to look at a fixation box. Participants were presented with two practice passages and practice comprehension questions before the trial items. Items were presented in random order. The entire study lasted approximately 30 minutes. Participants were debriefed at the end of the study.

1.7 | Data analysis

To examine the effect of our manipulation, we analysed several standard eye movement measures. Specifically, we examined *total passage* *reading time* (the time spent reading each passage), target word *gaze duration* (the sum of all fixation durations on a word during first-pass reading), target word *total word reading time* (the sum of all fixation durations on a word) and *return-sweep fixation durations* (the duration of fixations preceding and following a return-sweep).

Data were analysed using (Generalised) Linear Mixed-effects Models ([G]LMMs) constructed using the *lme4* package (version 1.1.30; Bates, Mächler, et al., 2015) in R (version 4.2.1; R Development Core Team, 2022). For each predictor, we report regression coefficients (*b*), standard errors (*SE*), *t*-values. We used the two-tailed criterion $|t| > 1.96$ for significance, corresponding to a .05 alpha-level. The *z*-values for generalised LMMs are interpreted similarly. Furthermore, we approximated *p*-values for each model using the *lmerTest* package (version 3.1.3; Kuznetsova et al., 2017). To conserve power lost to unnecessary complexity, we used a parsimonious approach to model the random effects structure (Bates, Kliegl, et al., 2015). All numerical variables were centred prior to analysis. For the categorical predictor of condition, we applied summed-to-zero contrasts using the *contr.sum*() function such that the intercept corresponded to the grand mean and the categorical predictor of condition corresponded to a main effect.

To evaluate the evidence for the critical null effects, we supplemented our analyses with Bayes factor analysis (for a review see Wagenmakers, 2007). Bayes Factors were computed by fitting Bayesian linear-mixed effects models using the *brms*() function from the *brms* package (version 2.17.0; Bürkner, 2017). The model structure matched the converged *(g)lmer*() models for each dependent variable. For each fixed-effect, we assumed uninformative priors *normal*(*0,1*). Each model had 12,000 iterations (with 2000 being discarded due to warmup). Consultation of the Rhat statistic indicated that each model had fully converged. For each fixed-effect, we then used the *hypothesis*() function to compute Bayes Factors (BF10), where BF10 > 3 indicates moderate, BF10 > 10 indicates strong, BF10 > 30 indicates very strong, and BF10 > 100 indicates extreme evidence for H1, while BF10 < 1/3 indicates moderate, BF10 < 1/10 indicates strong, BF10 < 1/30 indicates very strong, and BF10 < 1/100 indicates extreme evidence for the null hypothesis (Jeffreys, 1961). In addition to our Bayes Factor analysis in the main text, we report a sensitivity analysis in the *Supplemental Materials*. Overall, the results of Bayes Factor analyses were not influenced by the informativeness of priors.

Prior to analysis, fixations shorter than 80 ms or longer than 800 ms were excluded from the analysis (2.87% of fixations)– except for fixations which were shorter than 80 ms and within one character of the previous or subsequent fixation. These fixations were combined with the previous or subsequent fixation. For eye movement measures, we applied Hoaglin and Iglewicz's (1987) procedure to identify and remove outliers. This procedure defined outliers as data points that were 1.65 times the difference between the first quartile (Q1) and the third quartile (Q3), above or below the Q1 and Q3 values (e.g. lower boundary = Q1–1.65 × (Q3-Q1); upper boundary = Q3 + 1.65 × (Q3-Q1)). The selected cut-off criterion was 1.65, due to the expected rightward asymmetric distribution of eye movement data.

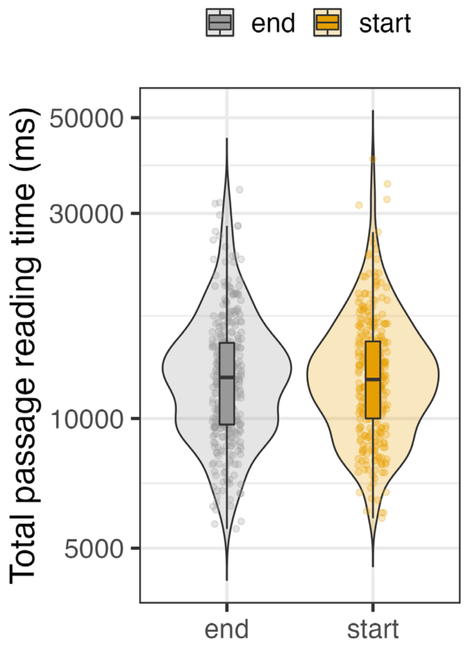

FIGURE 2 Total passage reading time per condition. Total passage reading times are shown in grey for the end of the line condition and in yellow for the start of the line condition. The *y*-axis is presented on a log scale.

All relevant data and analysis scripts are available on the Open Science Framework: https://osf.io/9bsc7/.

2 | RESULTS

On average, comprehension accuracy was 85.7% (*SD* = 35.00%) when target words appeared in a line-final position and 82.6% (*SD* = 37.95%) when they appeared in a line-initial position. A generalised LMM fitted to comprehension accuracy data (*glmer* (*accuracy* ~ *Condition* + (*1* | *participant*) + (*1* + *Condition* | *item*))) indicated that scores did not differ between presentation conditions, $b = 0.098$, $SE = 0.176$, $z = 0.55$, $p = 0.580$. Bayes Factor analysis yielded evidence in favour of the null, $BF10 = 0.259$, indicating that our manipulation did not influence comprehension accuracy.

2.1 | Total passage reading time

To examine the influence of our manipulation on global reading time, we fitted an LMM to total passage reading time. Prior to analysis, we removed reading times for words which differed between passages. These content differences always occurred at the very start of the passage, for example, Figure 1 we would remove *Em* and *Emily* when comparing reading times across passages. As shown in Figure 2, the mean passage reading time was 13,060 ms (*SD* = 4667 ms) when target words were line-final and 13,066 ms (*SD* = 4603 ms) when line-initial. The model fitted to log-transformed data (*lmer*(*log10*(*total* *passage reading time*) ~ *Condition* + (*1* | *participant*) + (*1* | *item*))) indicated that target word position had no influence on total passage reading time, $b = -0.003$, $SE = 0.003$, $t = -0.98$, $p = 0.326$. Bayes Factor analysis yielded evidence in favour of the null, $BF10 = 0.005$. Thus, positioning difficult to process, low-frequency words at either the very start or end of the line did not alter reading times across the passage.

2.2 | Target word reading times

When examining reading times for target words we calculated dependent measures by first excluding under-sweep fixations that occurred beyond the line-initial targets.[1] This enabled us to calculate first-pass reading measures (i.e. gaze duration) for cases where a corrective saccade was made prior to fixating a line-initial word. For the linear mixed-effects analysis, we included an additional random intercept for word token.

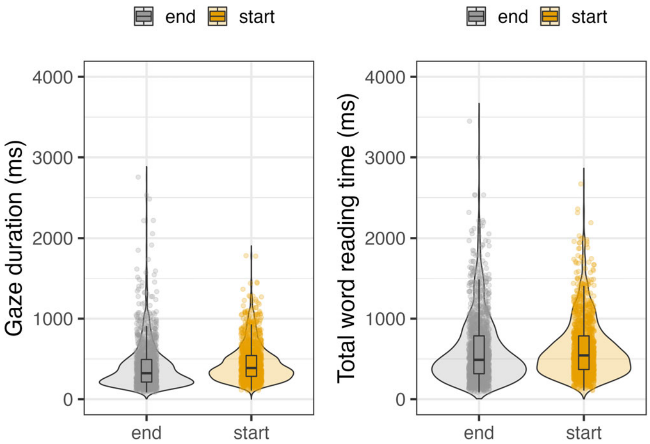

FIGURE 3 Gaze duration and total word Reading time per condition. Reading times are shown in grey for the end of the line condition and in yellow for the start of the line condition. The *y*-axis is presented on a log scale.

As shown in Figure 3, the mean gaze duration was 402 ms (SD = 286 ms) when target words were line-final and 444 ms (SD = 229 ms) when line-initial. The model fitted to log-transformed gaze duration (*lmer*(*log10*(*gaze duration*) ~ *Condition* + (*1* + *Condition* | *participant*) + (*1* | *item*) + (*1* + *Condition* | *word*))), indicated that gaze durations were significantly longer when targets were line-initial compared to when they were line-final, $b = -0.036$, $SE = 0.008$, $t = -4.79$, $p < .001$, $BF10 = 5.88$ e+01. The mean total word reading time was 605 ms (SD = 413 ms) when target words were line-final and 628 ms (SD = 354 ms) when line-initial. The model fitted to log-transformed total word reading time (*lmer*(*log10*(*total word reading time*) ~ *Condition* + (*1* | *participant*) + (*1* | *item*) + (*1* | *word*))) indicated that reading times were significantly longer when targets were line-initial compared to when they were line-final, $b = -0.021$, $SE = 0.004$, $t = -5.62$, $p < .001$, $BF10 = 1.16$ e+19. It is important to note the difference in best fitting models between the two measures. The best fitting model for gaze duration included a random slope for condition by participants, indicating that there was substantial between-participant variability in the magnitude of our manipulation on readers' gaze durations. The best fitting model for total time did not include a random slope for condition by participants which indicates that the variability in the size of the effect over participants was so small that including this random slope would have resulted in overfitting of our model.

2.3 | Return-sweep fixations

To assess the influence of our manipulation on return-sweep fixation durations, we divided reading fixations into four groups: intra-line (i.e. those not adjacent to a return-sweep), line-final, accurate line-initial (i.e. the first fixation on a line given that the next saccade moves towards the right), and under-sweep (i.e. the first fixation on a line

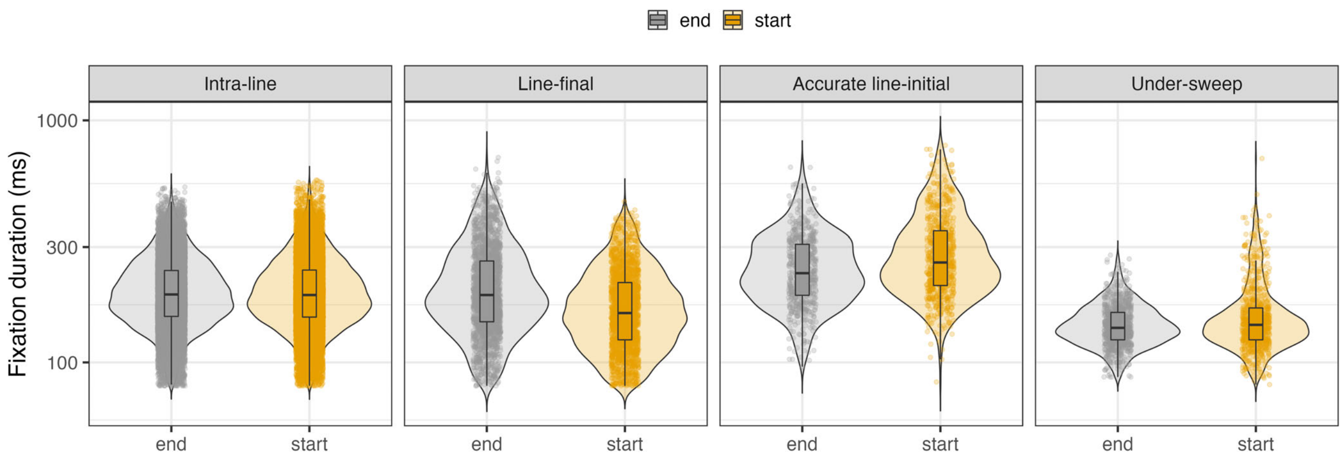

FIGURE 4 Fixation durations for each fixation population: Intra-line, line-final, accurate line-initial, and under-sweep. Fixation durations are shown in grey for the end of the line condition and in yellow for the start of the line condition. The y-axis is presented on a log scale.

TABLE 2 Durations (in milliseconds) of return-sweep fixations across conditions

Condition	Intra-line	Line-final	Accurate line-initial	Under-sweep
End	203 (67)	215 (95)	252 (87)	145 (30)
Start	204 (70)	176 (68)	294 (120)	159 (61)

Note: Standard deviations are shown in parentheses.

given that the next saccade moves towards the left). The distribution of fixation durations is shown in Figure 4 and their accompanying means are shown in Table 2. We then fitted an LMM (*lmer*(*log10*(*return-sweep fixation duration*) ~ *Condition* + (*1* | *participant*) + (*1* | *item*))) to each group of fixations.

Our manipulation did not significantly impact intra-line reading fixations, $b < .001$, $SE = 0.001$, $t = -0.54$, $p = 0.593$, $BF10 = 0.001$, with Bayes factor analysis yielding evidence for the null. The effect of our manipulation was significant for line-final fixations, $b = 0.040$, $SE = 0.003$, $t = 15.44$, $p < .001$, $BF10 = 1.46$ e+14, indicating that line-final fixations were longer when low-frequency target words were presented at the end of the line. Accurate line-initial fixation durations were also longer when low-frequency target words were at the start of the line, $b = -0.029$, $SE = 0.004$, $t = -7.37$, $p < .001$, $BF10 = 7.20$ e+14. Similarly, under-sweep fixation durations were longer when target words were at the start of the line, $b = -0.011$, $SE = 0.002$, $t = -5.18$, $p < .001$, $BF10 = 9.12$ e+13.

3 | DISCUSSION

Text wrapping across line boundaries often results in long, low-frequency words being positioned at the very start of lines. Given that long, low-frequency words typically receive longer reading fixations (see Rayner, 1998, 2009 for a review), it is surprising that no study (to our knowledge) has examined the effect that this procedure has on global and local reading behaviour. Addressing this empirically, our exploratory study placed low-frequency words either at the very end or the very beginning of lines. We then compared eye movements at both global and local levels. Starting globally, our manipulation did not influence total passage reading times. In fact, Bayes factor analysis provided strong evidence for the null hypothesis that reading times do not differ when low-frequency words are positioned at the start or end of a line. Equally important was the observation that comprehension accuracy did not differ between conditions. At the local (word) level, we observed longer reading times on target words when they were presented at the start rather than at the end of lines. Finally, regarding each specific population of return-sweep fixations, we reported that line-final fixations were longer when the low-frequency target word occurred in a line-final position. In contrast, line-initial fixations (both accurate and under-sweep) were longer when the target word was line-initial. Below we consider the implications of our findings.

Positioning words within a line of text is by no means a simple task. It will involve considering factors such as line length, spacing, kerning, and ligatures. Once words are positioned within a line of text, line breaking, or word/text wrapping occurs. Often this will result in long, low-frequency words being positioned at the very start of the line (Parker & Slattery, 2019). Coupled with reduced reading efficiency for line-initial words (i.e. longer reading times with similar passage comprehension accuracies,[2] Parker et al., 2017), this may cause disruption to reading at the passage level. Thus, we considered the implications of word positioning for low-frequency words in the current eye movement study to address the question *should word difficulty be used when determining line breaks?* The observed null results for measures of global reading (i.e. comprehension and total passage reading time) suggest that there is no apparent or consistent evidence that our manipulation had a reliable influence on global reading behaviour. However, making a strong conclusion that word difficulty should not be taken into account when determining line breaks may be premature given the uncertainty around estimates in the current study. The standard error of the mean (SEM) for total passage reading time was 226 ms when difficult to process, low-frequency words were line-final and 246 ms when difficult to process, low-frequency words were line-initial. The observed SEMs suggest that a theoretically larger difference in total passage reading times could potentially be observed in the future studies, implying that the true effect may be larger than the one we observed. Thus, based on the available evidence, we put forth the tentative suggestion that word difficulty may not need to be taken into account when determining line breaks. It is also important to note that we only examined the implications of positioning low-frequency target words at the start of the line during silent reading. It is entirely possible that when reading aloud readers may be faced with unique challenges whereby the eye voice span could be impacted more so by this manipulation. Past studies have already shown subtle differences in return-sweep behaviour when reading silently and aloud (i.e. Adedeji et al., 2021), so it remains an open question of whether the position of words will differentially affect fixations falling adjacent to return-sweeps.

The null findings for total passage reading time bear resemblance to findings reported by Liversedge et al. (2016), who compared eye movements across three writing systems (English, Chinese, Finnish). Despite clear differences in the readers' eye movements and the written forms of the linguistic stimuli, Liversedge et al. reported no statistically significant difference in the total reading times for the texts which were carefully constructed so that meaning was near identical across languages. This led to the conclusion that regardless of visual input from written language, readers converge on a similar semantic representation, and this is what drives total sentence reading times. While our null results could reflect a lack of statistical power, we adopt a similar argument and suggest that total passage reading times do not differ across conditions as the semantic information is identical across passages and these subtle local changes do not alter the representations that readers build.

While our manipulation had no statistically reliable effect on global reading, we observed several reliable differences at the local level. First, gaze durations and total word reading times were longer when target words were presented in a line-initial position. Like Parker et al. (2017) we believe the most parsimonious explanation for this observation is a lack of parafoveal preview for line-initial words. That is, readers benefit from preprocessing line-final words prior to direct fixation– something they cannot do for line-initial words due to how far these words are from the fovea prior to the return-sweep.

We also observed an effect of our manipulation on return-sweep fixations. Line-final fixations have consistently been reported to be shorter than intra-line reading fixations (Abrams & Zuber, 1972; Adedeji et al., 2021; Parker, Nikolova, et al., 2019; Parker, Slattery, et al., 2019). It has been argued that this reflects reduced lexical processing during line-final fixations while readers prioritise oculomotor programming (Kuperman et al., 2010). Consistent with this suggestion, Hofmeister (1997) reported that text degradation did not affect line-final fixation duration. If these fixations are uninvolved in lexical processing, then line-final fixations should be uninfluenced by word level properties. The fact that we report longer line-final fixation durations when low-frequency targets are positioned at the end of the line is at odds with such a claim. Instead, it suggests that differences in word-level properties do influence line-final reading fixations. It may, therefore, be time to abandon the claim that line-final fixations are uninvolved in lexical processing. Instead, the reduction in duration for line-final fixations may stem from a number of other sources: (1) line-final fixations are not impacted by processing difficulty stemming from upcoming words (due to mislocated fixations, parafoveal-on-foveal effects, etc.); (2) reduced lateral visual masking for line-final words; (3) a reduction in skipping costs during line-final fixations. It will be down to future studies to determine the extent to which each of these sources contributes to shorter line-final fixations through carefully crafted novel experimentation.

Regarding line-initial fixations, the data suggest that line-initial fixation durations were longer when target words were line-initial. Across the two conditions, accurate line-initial fixations will have been on a higher frequency word when target words occurred at the end of the line. Thus, we can assume any difference likely reflects a frequency effect. However, it is important to note that this may have also reflected some other components such as word length given that this was not controlled in the current study. The most striking finding regarding return-sweep fixation durations is the observation that under-sweep fixations were longer when target words were positioned at the very start of the line. Evidence has indicated that under-sweeps do not vary with lexical properties of the fixated word (Slattery & Parker, 2019), words adjacent to fixation (Parker et al., 2020), or reading skill (Parker & Slattery, 2021). Then why might we see that our manipulation influenced under-sweep durations? It is possible that differences in lexical properties across conditions may have resulted in this pattern of results. However, such an explanation would be difficult to reconcile with previous null findings. Instead, it may be that when targets are line-initial, readers land on target words and require an additional corrective saccade to reach a more optimal position for processing. By contrast, when target words are at the end of the line, readers' return-sweeps will land in a similar position but will fixate the second or third word on a line. As such, they will rapidly initiate a corrective saccade towards a new word (i.e. make an inter-word regression). It could be that white spaces between words cause readers to execute this corrective saccade more rapidly than in cases where they have already landed on the line-initial word. It is also important to note that, to date, the method for determining under-sweep fixations is overly simplistic. If a reader's initial return-sweep saccade is followed by a leftward saccade then the intervening fixation is classified as an under-sweep. However, we acknowledge that a percentage of these leftward saccades will likely be true reading regressions rather than corrective saccades. In such 'true regression' cases, we expect that lexical properties of the fixated word would impact the intervening fixation durations. What might lead to an increase in 'true regression' cases? Regressions are known to increase with text processing difficulty (for a review, see Bicknell & Levy, 2011) and having a long low-frequency line initial word would be one such form of increased difficulty. What might we expect to see if the under-sweeps for the start of the line condition were a mixture of corrections and true regressions? Prior research suggests that fixations prior to corrective saccades are very short (Becker, 1972; Tian et al., 2013) but that fixations prior to regressions which return the eyes to previously fixated words are similar or even longer than typical reading fixations (Henderson & Luke, 2012; Rayner et al., 2003; Weger & Inhoff, 2006). Indeed, an examination of Figure 4 hints at such a mixture as the difference between under-sweep fixation durations in the start and end conditions exist almost exclusively in the upper tails of the distributions. Future research may benefit from the use of Gaussian mixture modelling to improve the classification of 'under-sweeps'.

In conclusion, through a single exploratory eye movement study, we examined whether word difficulty (i.e. lexical frequency) should be considered when determining line breaks. This was accomplished by examining the eye movements of readers as they read passages where low-frequency target words were line-final or line-initial. While we found no statistically reliable differences in passage reading times across conditions it is difficult to make strong conclusions without narrow confidence intervals around estimates within our data. As such, we tentatively conclude that word difficulty may not need to be taken into account when determining line breaks and future work will be required to validate this finding. Moreover, we found robust local effects which replicate prior research further highlighting the immediacy of language processes on the control of eye movements during reading.

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CONFLICTS OF INTEREST

The authors declare that they have no conflict of interest.

DATA AVAILABILITY STATEMENT

The datasets generated and analysed during the current study are available in the Open Science Framework (OSF) repository, https://osf.io/9bsc7/.

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ENDNOTES

[1] These under-sweep fixations were removed due to the nature of gaze duration calculations. Once a fixation occurs on text beyond the target word the gaze duration measure ends. Therefore, under-sweep fixations that land beyond the target word would result in these targets not having a gaze duration.

[2] While a statistical comparison of the comprehension accuracies was not performed in Parker et al., 2017, we have conducted this analysis and found no significant effect of word position, $b = 0.625$, $SE = 0.374$, $z = 1.67$, $p = 0.094$, $BF10 = 1.316$.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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APPENDIX A

Here, we list our experimental stimuli, where target words are **bolded**. Each passage is shown in the line initial condition followed by the line-final condition. Comprehension questions and answers appear following each item.

Item 1

Jen was going to the flower shop to buy **foxgloves**
for her dad who was in the hospital with **leukemia**.
The cancer had spread to his lungs and **trachea**,
giving him only weeks to live. She was **inconsolable**
but tried to remain cheery, especially for her
father's sake.

Jennifer was going to the flower shop to buy
foxgloves for her dad who was in the hospital with
leukemia. The cancer had spread to his lungs, and
trachea, giving him only weeks to live. She was
inconsolable but tried to remain cheery, especially
for her father's sake.

Q: How long did her father have to live? - Days - Weeks - Months.

Item 2

Jeff and Jo were excited to be going to see **Arctic**
Monkeys play live at the O2 with their **audiologist**

friend Ed. They met him at the annual **psychophysics** conference where Jo was presenting a **dissertation** on hearing loss in babies.

Jeffrey and Jo were excited to be going to see **Arctic** Monkeys play live at the O2 with their **audiologist** friend Ed. They met him at the annual **psychophysics** conference where Jo was presenting a **dissertation** on hearing loss in babies.

Q: What was Jo's dissertation about? - Hearing loss - Sight loss - Mobility loss.

Item 3

York town centre includes a beautiful **arboretum** from the 18th century. It specialises in **conifers** mainly, and therefore may also be called a **pinetum**. It is currently home to more than twenty **subspecies** of pine trees.

Yorkshire town centre includes a beautiful **arboretum** from the 18th century. It specialises in **conifers** mainly, and therefore may also be called a **pinetum**. It is currently home to more than twenty **subspecies** of pine trees.

Q: The arboretum was from which century? - 17th - 18th - 19th

Item 4

At the wedding, Ann's uncle Ted gave the **newlyweds** a number of presents that included silver **utensils** and drapes. On the wedding day, she wore a **corsage** from her uncle, which she treasured as a **keepsake** that reminded her of him.

At the wedding, Annabelle's uncle Ted gave the **newlyweds** a number of presents that included silver **utensils** and drapes. On the wedding day, she wore a **corsage** from her uncle, which she treasured as a **keepsake** that reminded her of him.

Q: What was the bride's favourite gift from her uncle? - utensils - corsage - necklace

Item 5

NASA has been working on the problem of **deorbiting** space debris. Discarded satellites may **disintegrate** into small hazardous pieces in the **geostationary** orbit. Because these pieces can cause **irreversible** damage to spacecraft, finding a **sustainable** solution is crucial.

Virgin Galactic has been working on the problem of **deorbiting** space debris. Discarded satellites may **disintegrate** into small hazardous pieces in the **geostationary** orbit. Because these pieces can cause **irreversible** damage to spacecraft, finding a **sustainable** solution is crucial.

Q: Why is deorbiting space debris important? - It can fall to Earth - It can damage spacecraft - It takes up space

Item 6

Kim and Jeff got engaged last autumn at the **sawmill** museum. They had always enjoyed visiting **kooky** places and they wanted to get married at the **jute** museum in Ayr. At the wedding, Kim looked **angelic** as she walked down the aisle.

Kim and Jeffrey got engaged last autumn at the **sawmill** museum. They had always enjoyed visiting **kooky** places and they wanted to get married at the **jute** museum in Ayr. At the wedding, Kim looked **angelic** as she walked down the aisle.

Q: Where did the couple want to get married? - The jute museum - The courthouse - The sawmill museum

Item 7

Em was at the shopping centre looking for a **dustpan** for her aunt who had recently moved into a **prefab** in Bournemouth. The house included a large **scullery** which her aunt would equip with hydrogen **peroxide** and other cleaning products.

Emily was at the shopping centre looking for a **dustpan** for her aunt who had recently moved into a **prefab** in Bournemouth. The house included a large **scullery** which her aunt would equip with hydrogen **peroxide** and other cleaning products.

Q: What did the aunt plan on storing in the scullery? - sporting equipment - clothes - cleaning supplies

Item 8

Joe was really furious as he limped to the **washroom** and checked his reflection in the mirror. **Seething**, he ripped his jeans and examined his left **tibia** which was broken. The fracture was on the **posterior** surface of the bone.

Joseph was really furious as he limped to the **washroom** and checked his reflection in the mirror. **Seething**, he ripped his jeans and examined his left **tibia** which was broken. The fracture was on the **posterior** surface of the bone.

Q: Which bone had the man broken? - right tibia - left tibia - right fibula.

Item 9

I just met with Kim and Alex to discuss **baptising** their new baby. They wondered about the **ointment** used for the ceremony because the baby had **eczema** on her head and the ingredients could **exacerbate** the rash.

I just met with Kimberley and Alex to discuss **baptising** their new baby. They wondered about the **ointment** used for the ceremony because the baby had **eczema** on her head and the ingredients could **exacerbate** the rash.

Q: What could exacerbate the baby's rash? - ointment - oil - cream

Item 10

Ice hockey was developed in Scotland from **shinty**. The aim of ice hockey is to shoot a **vulcanised** rubber puck into a goal minded by a **goaltender**.

There exist different types of shots, **slapshot** being the hardest one.

Ice hockey was developed in the United Kingdom from **shinty**. The aim of ice hockey is to shoot a **vulcanised** rubber puck into a goal minded by a **goaltender**. There exist different types of shots, **slapshot** being the hardest one.

Q: What is the aim of ice hockey? - to score goals - to score hoops - to score points

Item 11

Figure skating includes jumps, turns and **spirals**. One of the most common elements is the **cantilever**. These days most male skaters perform **quadruple** jumps. Though common in exhibitions, the **backflip** is banned in competitions.

Olympic figure skating includes jumps, turns and **spirals**. One of the most common elements is the **cantilever**. These days most male skaters perform **quadruple** jumps. Though common in exhibitions, the **backflip** is banned in competitions.

Q: Which element is not allowed in competitions? - cantilever - quadruple jump - backflip

Item 12

Sam enjoyed buying nice things such as **candelabras** to show off his wealth. He bought a new **wristwatch** recently because he felt the old one was **antiquated** and he wanted to be absolutely sure the **townspeople** knew he was fashionable.

Samuel enjoyed buying nice things such as **candelabras** to show off his wealth. He bought a new **wristwatch** recently because he felt the old one was **antiquated** and he wanted to be absolutely sure the **townspeople** knew he was fashionable.

Q: Who did he want to impress with expensive things? - townspeople - his parents - neighbours

Item 13

Ben was feeling nervous because of the **trespassing** incident last month. He had always been **obedient** but now he did not listen and ended up **endangering** his job. If his boss had not been so **authoritative** and strict, maybe things would have gone differently.

Benjamin was feeling nervous because of the **trespassing** incident last month. He had always been **obedient** but now he did not listen and ended up. **endangering** his job. If his boss had not been so **authoritative** and strict, maybe things would have gone differently.

Q: Why was he in danger of losing his job? - trespassing - drunk driving - burglary

Item 14

Detectives Smith and Beckett found the **dismembered** body in the flat. There had been a real **bloodbath** in the bedroom. All four of the body's **extremities** had been cut off with most likely a **machete**, according to the pathologist.

Detectives Esposito and Beckett found the **dismembered** body in the flat. There had been a real **bloodbath** in the bedroom. All four of the body's **extremities** had been cut off with most likely a **machete**, according to the pathologist.

Q: In which room was the body found? - bedroom - bathroom - sitting room

Item 15

Beth worked really hard to land a great **internship**. She knew that at first she would be a **lackey**, however it would get her a start. It would **entail** filing papers and searching for any **irregularities** in the data.

Bethany worked really hard to land a great **internship**. She knew that at first she would be a **lackey**, however it would get her a start. It would **entail** filing papers and searching for any **irregularities** in the data.

Q: What duties were part of the internship? - customer service - filing - transport

Item 16

Ray's nightmare was finally over so he was **fervent** about his future. For two years he had been **stalked** but just last weekend the stalker was **apprehended** and now he was ready to start a new, **uncomplicated** life in the country.

Raymond's nightmare was finally over so he was **fervent** about his future. For two years he had been **stalked** but just last weekend the stalker was **apprehended** and now he was ready to start a new, **uncomplicated** life in the country.

Q: Why was the man excited? - his girlfriend was visiting - his stalker had died - his stalker was arrested

Item 17

Matt was tired of listening to his mother **whinging** because their garden was invaded by hungry **racoons** who ate her beloved, prize winning yellow **azaleas**. He went to the hunting store to buy an old **crossbow** to kill the racoons.

Matthew was tired of listening to his mother **whinging** because their garden was invaded by hungry **racoons** who ate her beloved, prize winning yellow **azaleas**. He went to the hunting store to buy an old **crossbow** to kill the racoons.

Q: With what was the man going to kill the raccoons? - poison - crossbow - gun

Item 18

Richard wanted to quit his job to become a **juggler**. He was currently working in a bank as an **auditor** but he strongly felt his true passion was **busking**

in the street. One day he hoped to juggle **rapiers.**
for a living.
Richard Bell wanted to quit his job to become a **juggler**. He was currently working in a bank as an **auditor** but he strongly felt his true passion was **busking** in the streets. One day he hoped to juggle **rapiers** for a living

Q: What did he want to juggle? - torches - bowling pins - rapiers

Item 19

Mike had recently been given an old **encyclopaedia**
by his Auntie. He instantly loved the **artefact**
It wasn't long before he started **manoeuvring**
between pages. He examined the page on **haemoglobin**
and studied the diagram intently
Michael had recently been given an old **encyclopaedia** by his Auntie. He instantly loved the **artefact**. It wasn't long before he started **manoeuvring** between pages. He examined the page on **haemoglobin** and studied the diagram intently

Q: What did the man study in the book? - a diagram - a figure - a pie chart

Item 20

Sue was excited to finally reach the open **hilltop**
She took in the sights and observed a cute **vinery**
off to the right. She also saw a pack of **dingos**
stalking their prey. Down the mountain ran a **turbid**
stream which she knew to avoid
Susanna was excited to finally reach the open **hilltop**. She took in the sights and observed a cute **vinery** off to the right. She also saw a pack of **dingos** stalking their prey. Down the mountain ran a **turbid** stream which she knew to avoid

Q: What could be seen from the hilltop? - a garden - a vinery - a stable