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# Eye movements when reading disappearing text: is there a gap effect in reading?

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**Abstract**

Readers' eye movements were monitored when they read either normal sentences or sentences with masked or disappearing text (in which the fixated word disappeared or was masked after 60 ms). The goals of the research were to investigate (1) whether a gap effect occurred in reading and (2) the influence of linguistic and visual factors on oculomotor control. The results of a number of global analyses of eye movements under disappearing text conditions clearly demonstrated that there is no gap effect in reading. However, comparative analyses across a number of local measures in the experiments indicated that cognitive/lexical processes, as well as the continual uptake of visual information, influence eye movement control during reading. A persistent visual object throughout fixation caused refixations and even when a fixated word had disappeared (or been masked), there were significant effects of word frequency and word length.


## 1. Introduction

When readers see text for only the first 50–60 ms of each fixation before a masking pattern appears, reading proceeds quite normally (Ishida & Ikeda, 1989; Rayner, Inhoff, Morrison, Slowiaczek, & Bertera, 1981; Slowiaczek & Rayner, 1987). Rayner et al. (1981) argued that this does not mean that word identification or other higher level processes associated with reading are completed in 50–60 ms. Rather, they suggested that the information needed for reading enters the processing system very quickly and readers are able to comprehend the text as long as it is available for 50–60 ms before the mask comes on (and the text is removed). Given that fixations are, on average, between 220 and 250 ms, Rayner et al. argued that the remainder of the time during a fixation is spent programming the subsequent eye movement, integrating characteristics of the text at higher levels, and pre-processing information to the right of the currently fixated word. Here, we report three experiments that extend the work of Rayner et al. Specifically, we used a version of the eye contingent change paradigm (McConkie & Rayner, 1975; Rayner, 1975) to make text disappear before the reader's eyes (rather than masking it).

In Experiment 1, on half of the trials participants read a sentence presented normally on a visual display unit. However, in the disappearing text condition, 60 ms after a word was fixated, it disappeared. The remainder of the sentence remained on the screen after the word disappeared and when the reader moved his/her eyes to look at the next (or any other) word in the sentence, it too disappeared after 60 ms (with the word that had previously been fixated reappearing immediately). In this way, the reader could fixate the sentence as he/she would when reading it normally, but each word of the text disappeared before their eyes as they read.

Rayner, Liversedge, White, and Vergilino-Perez (2003) found that reading under such conditions is surprisingly easy and language processing appears to proceed unimpaired. They found the duration of a fixation is influenced by a word's frequency even after it has disappeared. Here, we manipulated word frequency, but we also manipulated word length. Thus, each

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sentence contained a long or short target word and a high or low frequency target word.

We also used the disappearing text manipulation to investigate the possibility that reading rate might be increased by making fixated words disappear shortly after fixation onset. There are good theoretical reasons to believe that making text disappear in this manner could speed up reading rate. Saslow (1967) first showed that offsetting a fixation stimulus prior to the onset of a target stimulus caused a reduction in saccade latencies. Subsequently, Cohen and Ross (1977) (see also Kingstone & Klein, 1993a, 1993b; Ross & Ross, 1980, 1981; Walker, Kentridge, & Findlay, 1995) showed that when participants are fixating a stimulus and are about to make a saccade to a target elsewhere in the visual field, the time to make the saccade is reduced if the stimulus that is currently fixated disappears compared with when it does not. Thus, the saccade latency is shorter when the fixation cross disappears than when the fixation cross remains visible.

It is generally agreed that this phenomenon, the *gap effect*, is comprised of two separable components (Kingstone & Klein, 1993a; see also Findlay & Walker, 1999; Pratt, Bekkering, & Leung, 2000): a reduction in saccade onset latencies due to the removal of foveal stimulation prior to the onset of the target (the fixation offset effect) and an additional reduction due to a general warning that an eye movement is required (afforded by the temporal gap between foveal offset and non-foveal target onset). Since the gap effect has been shown to occur for involuntary pro-saccades to fixation onset as well as cognitively controlled voluntary anti-saccades (Abrams, Oonk, & Pratt, 1998; Craig, Stelmach, & Tam, 1999; Forbes & Klein, 1996), it seems plausible that saccades generated during reading could be influenced by fixation offsets in a similar way.

Given that a 60 ms presentation of text is sufficient for reading to proceed quite normally (Rayner et al., 1981, 2003), and given that the disappearing text paradigm involves the removal of the text that falls on the fovea shortly after fixation onset, then the conditions of Experiment 1 provide the opportunity for us to investigate the possibility that a gap effect might occur during reading. Specifically, the removal of a fixated word prior to saccade onset could, in principle at least, speed saccade onsets, thereby reducing reading times.

The possibility of obtaining such an effect, however, rests on the assumption that a gap effect can be obtained during any sequence of scanning eye movements across a horizontal array. To date, there has been no such demonstration. Instead, the vast majority of studies investigating the gap effect have required participants to fixate a central location or fixation marker and then make a single saccade to a non-foveal location after a target onset has occurred. Therefore, to investigate whether it was at least possible to obtain a gap effect during horizontal sequential scanning, it was necessary to carry out a control experiment (Experiment 2) in which participants were simply required to scan along an array of disappearing X's. We also conducted a second control experiment (Experiment 3) in which we masked the word with X's after 60 ms. This procedure ensured that readers could not process an iconic trace (Sperling, 1960) of the word. [1]

## 2. Method

### 2.1. Participants

Sixteen members of the University of Durham community participated in Experiment 1. In Experiments 2 and 3, eight participants from the same population took part in each experiment. All were native English speakers with normal or corrected to normal vision. They were paid to participate, and all were naïve in relation to the purpose of the experiment; no participant took part in more than one of the three experiments.

### 2.2. Materials and design

In Experiment 1 there were 40 experimental sentences, each of which included two critical words. The first critical word was 4 or 10 letters long and the second critical word was frequent or infrequent (and always 6 letters long). The text was either presented normally or such that individual words disappeared 60 ms after they were fixated. The words only reappeared once a saccade was made either to the left or right out of the word. If readers refixated on the word (i.e., made a second fixation on the word prior to fixating a different word), it did not reappear. Fig. 1 shows an example of the disappearing text condition. Word length, word frequency, and text presentation were manipulated within participants and items.

Word frequencies were calculated using the CELEX English word form corpus (Baayen, Piepenbrock, & Gulikers, 1995). There was no difference in word frequency between the 4 ($M = 47$, $SD = 60$, range: 0–218) and 10 letter words ($M = 35$, $SD = 40$, range = 0–197), $t(39) = 1.11$, $p > 0.25$. The frequent words ($M = 105$, $SD = 162$, range: 18–970) were significantly higher frequency than the low frequency words ($M = 1$, $SD = 2$, range: 0–7), $t(39) = 4.06$, $p < 0.001$.

Each sentence occupied a single line no longer than 80 letters (see Table 1). The critical 4 or 10 letter word was preceded by a 6 letter word and followed by a 5 or 6 letter

[1] It is important to note that Rayner et al. (2003) carried out a "shutter test" (Irwin, Yantis, & Jonides, 1983) that ensured phosphor persistence did not enable participants to see a fading image of the word after it had disappeared from the screen.

| | |
|---|---|
| He found the secret manuscript inside the little<br>* | Beginning of fixation |
| He found the        manuscript inside the little<br>* | After 60 ms |
| He found the secret manuscript inside the little<br>* | New fixation |
| He found the secret            inside the little<br>* | After 60 ms |

Fig. 1. Example of disappearing text. The asterisk indicates fixation location. Thus, when the reader fixates on *secret*, it disappears after 60 ms and it is not presented again until the reader makes an eye movement to a new word. When the reader makes an eye movement and fixates on *manuscript*, it likewise disappears after 60 ms.

Table 1
Example sentences

| | |
|---|---|
| 1. | Yesterday the office *boss/supervisor* moaned about the broken/snazzy equipment upstairs |
| 2. | Sam wore the horrid *coat/spectacles* though his pretty/demure girlfriend complained |
| 3. | He found the secret *swag/manuscript* inside the little/sturdy farmhouse on the hill |
| 4. | A proper *gift/collection* scheme boosted the annual/frugal donations to the charity |
| 5. | The clumsy *lads/volunteers* asked the random/nimble gentleman to help carry the table |

Short and long target words are shown in italics. Frequent and infrequent target words are underlined.

word. The critical frequent or infrequent word was followed by a 9 or 10 letter word. Two lists of 50 sentences were constructed and eight participants were randomly allocated to each list. Each list included 40 experimental sentences of which half included a 4 letter critical word and half a 10 letter critical word; half included a frequent critical word and half an infrequent word. The sentences were presented in a fixed random order, but in two blocks with 20 experimental sentences in each block. One block was presented in normal text and one block was presented in disappearing text format. The order of blocks was counterbalanced across participants. Five filler sentences were at the beginning of each block and there were 16 comprehension questions.

In Experiment 2, the stimuli were changed such that every letter in each sentence was replaced by an X (with spaces between words preserved). Participants were instructed to scan the X's and to press a button when they reached the end of the line. In one condition, the X's remained on the screen throughout the trial; in the other, the X's disappeared 60 ms after fixation on that group of X's. In Experiment 3, the materials and procedure were identical to Experiment 1 except than that instead of each word disappearing 60 ms after fixation, the word was masked by X's. In Experiments 2 and 3, four participants were randomly allocated to each list.

### 2.3. Apparatus

Eye movements were sampled every ms by a Fourward Technologies Dual Purkinje Generation 5.5 eye tracker with spatial resolution of 10 min of arc. Viewing was binocular, but only the right eye was monitored. The sentences were displayed as white letters (in lower case except for where capital letters were appropriate) on a black background on a Phillips 21B582BH 24 in. monitor at a viewing distance of 1 m; 5 letters subtended 1 deg of visual angle. The monitor had a P22 phosphor with a decay rate to 0 in less than 1 ms. The monitor and the eyetracker were interfaced with a Phillips Pentium III PC that controlled the experiment.

### 2.4. Procedure

In Experiments 1 and 3, participants were instructed to read the sentences in order to understand them. After reading each sentence, they pressed a button to continue and used a button box to respond yes/no to comprehension questions. A bite bar and head restraint were used to minimize head movements. In Experiment 2, participants fixated the left end of the array of X's at the start of each trial and scanned it horizontally until they reached the end of the array. They were told that it was not necessary to fixate each group of X's in the array, but it was important to fixate most of them. The initial calibration procedure lasted about 5 min and the calibration accuracy was checked after every trial. An experiment lasted about 30 min.

## 3. Results

Consistent with most eye movement research on reading (Liversedge & Findlay, 2000; Rayner, 1998) a number of different measures were examined. Global measures will be first examined for Experiment 1 followed by a set of local measures of processing for the critical word length and word frequency target words. For the global measures, we report measures of reading time, number of fixations, saccade length, word skipping probability, refixations (the probability of making another fixation on a word before leaving the word), and number of regressions across the entire sentence. For the local measures, we report measures of first fixation duration (the duration of the first fixation on a word independent of the number of fixations on that word), gaze duration (the sum of all fixations on a word before the eyes move to another word), as well as word skipping and refixation probability for both the high/low frequency target words and the long/short target words. Fixations shorter than 80 ms and longer than 1200 ms were excluded from the analyses, which are based on variability due to participants ($t1, F1$) and items ($t2, F2$).

Although participants in Experiment 2 were required to scan arrays of X's, measures of scanning time were computed according to exactly the same definitions as each of the reading time measures, and the strings of X's that took the place of the words were treated as regions in exactly the same way that the words of the sentences in Experiments 1 and 3 were treated. Therefore, for simplicity's sake, we will refer to reading time measures in all of the experiments, even though in Experiment 2 participants scanned X's rather than read sentences. We compared the data from Experiments 2 and 3 with Experiment 1 using ANOVA's with Experiment as a between participants variable. For these comparative analyses, rather than provide an extensive list of all the measures reported in Experiment 1, we focus on measures that were most informative with respect to similarities and differences in eye movement behaviour.

## 4. Experiment 1: global measures

### 4.1. Sentence reading time

Replicating results reported by Rayner et al. (2003), there was no difference in how long it took to read the sentences as a function of whether the text was normal (3286 ms) or disappeared (3327 ms), $ts < 1$. Thus, as in the case when text is masked after 50–60 ms (Ishida & Ikeda, 1989; Rayner et al., 1981; Slowiaczek & Rayner, 1987), readers read quite normally when text disappears after 60 ms. Furthermore, comprehension accuracy did not differ between the normal text (86% correct) and disappearing text (84%) conditions, $ts < 1$.

Importantly, there was no evidence for anything resembling a gap effect. Although some participants' intuitions were that they read disappearing text faster than normal text, the reading time data do not match their intuitions. However, some participants felt that they started out reading each sentence faster in the disappearing text condition than in the normal condition, but then slowed down (perhaps for comprehension reasons). To check on this, we divided each sentence into 10–12 different regions (corresponding to each word in the sentence). We then examined the first pass reading time (gaze duration) for each region, as well as the total time spent in each region [2]. Fig. 2 shows that there were no systematic differences in these two different measures of reading time per region for the disappearing and normal text.

[2] Note that gaze durations do not include fixations made after a regressive saccade whereas total times do.

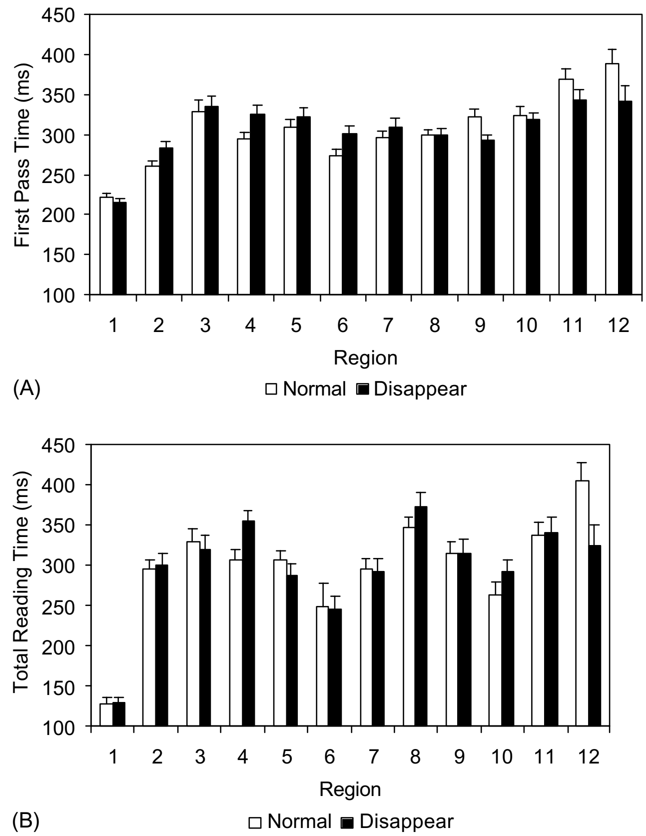


Fig. 2. Panel A shows mean gaze duration and Panel B shows mean total reading time in each region for disappearing and normal text.

### 4.2. Fixation durations and number of fixations

While there were no differences in reading time or comprehension between normal and disappearing text, readers adopted slightly different strategies for reading disappearing text compared to normal text. Specifically, their average fixation duration when reading disappearing text (264 ms) was longer than when reading normal text (248 ms), $t1(15) = 2.37$, $p < 0.05$; $t2(39) = 2.7$, $p < 0.01$. This was compensated for by the fact that they made fewer fixations (12.7 per sentence) when reading disappearing text than when reading normal text (13.6 per sentence), $t1(15) = 2.11$, $p = 0.052$; $t2(39) = 2.19$, $p < 0.05$. There was no difference in the probability of skipping on first pass: readers skipped words 32% of the time when reading disappearing text and 30% of the time when reading normal text, $ts < 1$.

To more closely examine the fixation time indices, we examined the mean duration of the first fixation on each region (or word) as well as the mean gaze duration and mean total time for each region. First fixation durations averaged 280 ms for disappearing text compared to 255 ms for normal text, $t1(15) = 4.83$, $p < 0.001$; $t2(39) = 6.56$, $p < 0.001$. However, gaze duration and total time did not differ between the two conditions (gaze duration: 307 ms for disappearing text and 305 ms

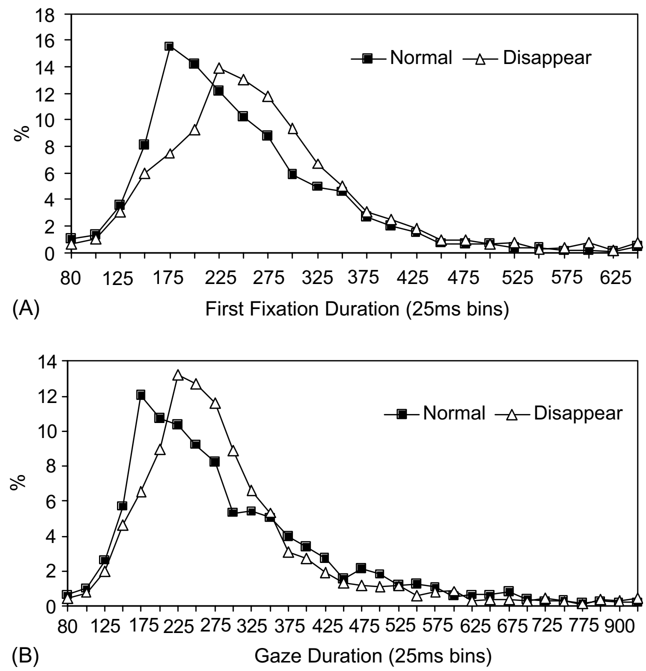


Fig. 3. Panel A shows the frequency distributions for gaze durations and Panel B shows the frequency distributions for total reading time for normal and disappearing text.

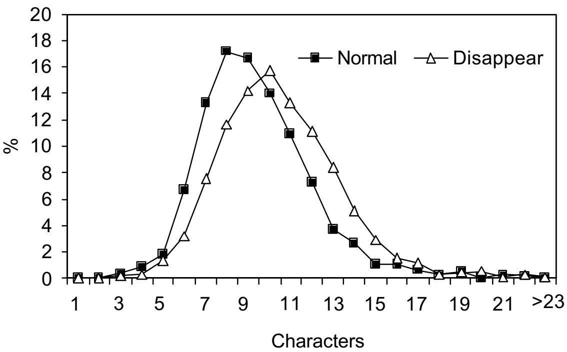


Fig. 4. Frequency distribution for inter-word saccade lengths.

for normal text; total time: 391 ms for disappearing text and 375 ms for normal text), $ts < 1.32$. Fig. 3 shows the frequency distribution for the first fixation durations and gaze durations. In the first fixation distribution, there are clear signs of a distribution shift as the disappearing text distribution is clearly below the normal for fixations under 225 ms and then above it after that. However, for the gaze duration distribution there appear to be two crossovers so that the normal distribution has slightly more longer gaze durations than the disappearing text distribution. This is due to the fact that readers were more likely to make multiple first pass fixations on a word in the normal text condition (14% of the time) compared to the disappearing text condition (7% of the time), $t1(15) = 5.56$, $p < 0.001$; $t2(39) = 9.08$, $p < 0.001$.

In essence, although the sentence reading time was the same for disappearing and normal text, disappearing text yielded slightly longer average fixations across the sentence and longer first fixations on a word. However, there was also a tradeoff in which readers made fewer fixations with disappearing text, as well as fewer multiple and regressive fixations (see below) on a word. This tradeoff yielded equivalent sentence reading times and equivalent gaze durations.

### 4.3. Saccade length

Given that readers made fewer fixations when reading disappearing text than normal text, it is not surprising that the average forward saccade length was longer for disappearing text (9.1 letters) than normal text (8 letters), $t1(15) = 5.66$, $p < 0.001$; $t2(39) = 6.85$, $p < 0.001$. Fig. 4 shows that the frequency distribution for saccade lengths is shifted such that there are more longer saccades for disappearing than normal text.

### 4.4. Refixations and regressions

We already noted that readers were less likely to refixate on a word when reading disappearing text than when reading normal text. Of course, in the disappearing text condition a refixation would not be functional since new text would not appear until another word was fixated. Yet it is interesting that, of the words that were fixated on first pass, 10% of the time readers did refixate on the word that had disappeared compared to 20% of the time in the normal text condition, $t1(15) = 5.4$, $p < 0.001$; $t2(39) = 9.26$, $p < 0.001$.

To examine refixations more carefully, we examined 9–10 letter words (where the probability of refixating is much higher than shorter words). This analysis revealed two interesting results: (1) the size of the refixation intraword saccade did not differ as a function of whether or not the text was normal or disappeared (being roughly 5 letter spaces in each case); (2) readers were much more likely to refixate to the left in the disappearing text condition than in the normal text condition. Specifically, if a reader refixated a word in the normal text condition, 88% of the time they did so with a refixation to the right of the original fixation and only 12% of the time to the left. However, with disappearing text, the refixation probabilities were 56% to the right and 44% to the left. The difference in probabilities to move to the left via a refixation differed between normal and disappearing text, $t1(10) = 2.95$, $p < 0.05$; $t2(26) = 3.88$, $p < 0.001$.

In the disappearing text condition refixations provided no information about the word that was presented on the prior fixation. There are two possible explanations for why readers may have made refixations when the text disappeared. The first is consistent with prior research by Vergilino and Beauvillain (2000) showing that a refixation saccade is pre-programmed on the basis of the intrinsic properties of a word (such as its length). Thus, according to this view, readers program a second fixation on a long word prior to actually fixating on it; when they program their saccade into a long word, a second saccade is also programmed to land later in the word. However, this second saccade can easily be cancelled if the word is identified on the first fixation. A second possibility is that the refixations are not preplanned, but planned and executed after the word has initially been fixated. For example, if linguistic processing requires that the reader spends longer on a word to process it, then this may be achieved either through the extension of the initial fixation or by making a refixation. Thus, even though there is no visual stimulus after 60 ms, it is still possible that readers increased the time they spent processing a word by making a refixation rather than extending the duration of the initial fixation.

Finally, readers made more regressions when the text disappeared (1.9) than when it did not (1.7), $t1(15) = 1.57$, $p > 0.05$; $t2(39) = 3.07$, $p < 0.005$. This result suggests that the increased number of fixations in the normal compared with the disappearing text condition stems primarily from first pass refixations rather than regressive refixations on words.

## 5. Experiment 1: local measures

### 5.1. Frequency effects

A 2 (frequency: high vs low)×2 (text: normal vs disappearing) ANOVA revealed that readers first fixations on low frequency words (283 ms) were longer than on high frequency words (268 ms), $F1(1, 15) = 4.74$, $p < 0.05$; $F2(1, 39) = 7.18$, $p < 0.05$. They also looked longer at disappearing text (286 ms) than normal text (265 ms), $F1(1, 15) = 12.52$, $p < 0.01$; $F2(1, 39) = 16.25$, $p < 0.001$, but there was no interaction, $F$s $< 1$ (see Table 3).

There was also a frequency effect in gaze duration as readers looked longer at the low frequency words (322 ms) than the high frequency words (283 ms), $F1(1, 15) = 10.17$, $p < 0.01$; $F2(1, 39) = 21.92$, $p < 0.001$. However, as with the results of the global analysis there was no effect of text ($F$s $< 1$). It does appear on the surface that there was a tendency towards an interaction. That is, the frequency effect was somewhat larger (50 ms) for the normal text condition than for the disappearing text condition (27 ms). However, the interaction was not significant ($p$s $> 0.10$). Indeed, close examination of the data revealed that much of this tendency was due to three participants; when they were removed from the analysis the size of the frequency effect was much more similar across text conditions. Furthermore, in Rayner et al. (2003), the size of the frequency effect was identical in the normal and disappearing text conditions.

As in the global analysis (based on all words in the sentence), the reason that the gaze duration did not differ as a function of text condition was that readers were more likely to make a single fixation on the target word in the disappearing text condition and multiple fixations in the normal text condition. For the skipping data, there was a hint that frequent words were skipped more often, but the effect was not significant, $F1(1, 15) = 3.65$, $p = 0.075$, $F2(1, 39) = 1.89$, $p > 0.05$. There was no reliable effect of text condition and no interaction between the two (all $F$s $< 1$). For those cases in which the critical word was fixated during first pass we found that readers were more likely to make a refixation when a normally presented word was fixated (16%) than when a disappearing word was fixated (6%), $F1(1, 15) = 13.5$, $p < 0.005$; $F2(1, 39) = 14.02$, $p = 0.001$. They were also less likely to make a refixation on a frequent word (7%) than on an infrequent word (15%), $F1(1, 15) = 15.5$, $p < 0.005$; $F2(1, 39) = 11.27$, $p < 0.005$. However, these effects were qualified by a frequency by text condition interaction, $F1(1, 15) = 5.51$, $p < 0.05$; $F2(1, 39) = 6.99$, $p < 0.05$. When the words disappeared there was no difference in refixations on frequent and infrequent words ($t$s $< 1$), but when the text was presented normally, readers refixated infrequent words more often than frequent words, $t1(15) = 3.41$, $p < 0.01$; $t2(39) = 3.98$, $p < 0.001$. The interaction indicates that readers modulated their refixation rates on high and low frequency words contingent on whether the text disappeared or not. When the word remained visible, refixations were more likely for low than for high frequency words. However, when there was no word present to refixate, there was no difference.

### 5.2. Word length effects

A 2 (length: short vs long)×2 (text: normal vs disappearing) ANOVA for first fixation duration revealed that readers' fixations were longer for disappearing text (291 ms) than normal text (257 ms), $F1(1, 14) = 4.56$, $p = 0.051$; $F2(1, 33) = 13.44$, $p < 0.001$. While there was no effect of length (see Table 4), there was a text by length interaction, $F1(1, 14) = 5.5$, $p < 0.05$; $F2(1, 33) = 6.08$, $p < 0.05$. The nature of this interaction was that there was no difference in first fixation duration between short (295 ms) and long words (286 ms) in the disappearing text condition, ($t$s $< 1$), coupled with shorter fixations on short words (239 ms) than on long words (275 ms) in the normal condition, $t1(14) = 3$, $p < 0.01$, $t2(37) = 3.23$, $p < 0.01$. This interaction suggests that when readers fixate a foveal visual stimulus that persists throughout the fixation, then fixation durations are extended to an extent that is proportional with the physical size of the foveal stimulus. By contrast, when the foveal stimulus is terminated early during the fixation then the size of the foveal stimulus does not modulate first fixation duration.

For gaze duration, there was no main effect of text ($F$s $< 1$). There was a significant effect of length, $F1(1,14) = 16.02$, $p < 0.001$; $F2(1,33) = 35.99$, $p < 0.001$. Furthermore, the interaction was significant, $F1(1,14) = 10.37$, $p < 0.01$; $F2(1,33) = 10.97$, $p < 0.01$ and was driven by the fact that the size of the length effect was much larger for the normal text (164 ms), $t1(14) = 6.15$, $p < 0.001$, $t2(37) = 7.52$, $p < 0.001$, than for the disappearing text (69 ms), $t1(15) = 1.53$, $p = 0.146$, $t2(36) = 2.37$, $p < 0.05$. This is again consistent with the notion that persistent visual stimulation during fixation produced gazes proportional to the length of the fixated word.

For the skipping data, not surprisingly, short words were skipped more often than long words, $F1(1,15) = 83.59$, $p < 0.001$, $F2(1,39) = 127.86$, $p < 0.001$. But, whether or not the text was normal or disappearing had no effect ($F$s $< 1$), and the interaction was non-significant ($p$s $> 0.07$).

We computed the probability of making a refixation on the critical word length region when the region was fixated during first pass, and found a main effect of length, $F1(1,14) = 39.65$, $p < 0.001$, $F2(1,34) = 55.08$, $p < 0.001$, a main effect of text, $F1(1,14) = 9.11$, $p < 0.01$, $F2(1,34) = 12.97$, $p < 0.001$, and an interaction, $F1(1,14) = 17.81$, $p < 0.01$, $F2(1,34) = 16.92$, $p < 0.001$. There was no difference in the probability of refixating short words for disappearing and normal text ($t$s $< 1$), but there were significantly more refixations on the long words when the text was normal compared to when it disappeared, $t1(15) = 3.33$, $p < 0.01$, $t2(39) = 4.9$, $p < 0.001$.

The global and local analyses from Experiment 1 suggest two important points. First, consistent with Rayner et al. (2003), we found clear evidence that linguistic processing primarily influenced how long readers looked at words independent of whether the text was normal or disappeared. Second, we found no evidence consistent with a gap effect in reading. To further explore this issue, we turn to a comparison of the results of Experiment 2 with Experiment 1.

## 6. Comparative analyses of Experiments 1 and 2

To compare eye movement behaviour during reading with scanning of arrays of normal and disappearing X's, we conducted 2 (Experiment: words vs X's)$\times$2 (Text: normal vs disappearing) ANOVAs. If eye movement behaviour differs when words are read compared with X's being scanned for normal and disappearing stimuli, then we should obtain an interaction between the two variables. The data are shown in Table 2.

Total sentence reading times were longer for the sentences in Experiment 1 (3307 ms) than for arrays of X's in Experiment 2 (2609 ms), $F1(1,22) = 4.98$, $p < 0.05$; $F2(1,39) = 179.27$, $p < 0.001$. Presumably, the additional time associated with reading compared with scanning X's reflects linguistic processing required for comprehension of the text that did not occur during the scanning of X's. Importantly, there was no main effect of text, and no interaction between text and experiment (all $F$s $< 1$) indicating that while readers took less time to scan X's than to read, processing time was not reduced when the stimulus disappeared compared with when it did not.

Readers made significantly more fixations in the non-disappearing (11.8) than the disappearing (10.9) conditions $F1(1,22) = 5.16$, $p < 0.05$; $F2(1,39) = 21.61$, $p < 0.001$, and they also made significantly more fixations in the text (13.2) than in the X conditions (9.5), $F1(1,22) = 15.02$, $p = 0.001$; $F2(1,39) = 319.58$, $p < 0.001$,

Table 2
Global measures

| Exp. | Presentation | Total RT | No. fixations | Fix dur | FFD | Gaze | TT | Regressions | Prob. skip | Prob. refix |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 Reading | Normal | 3286 (898) | 13.6 (3.4) | 248 (102) | 255 (94) | 305 (148) | 375 (261) | 1.7 (1.2) | 0.30 | 0.20 |
| | Disappearing | 3327 (1109) | 12.7 (4.3) | 264 (46) | 280 (106) | 307 (148) | 391 (251) | 1.9 (1.4) | 0.32 | 0.10 |
| 2 Scanning | Normal | 2552 (899) | 9.9 (2.6) | 257 (53) | 268 (105) | 312 (149) | 314 (152) | 0.1 (0.3) | 0.27 | 0.17 |
| | Disappearing | 2666 (1021) | 9.1 (2.1) | 288 (79) | 308 (136) | 332 (147) | 334 (150) | 0.2 (0.4) | 0.29 | 0.11 |
| 3 Reading | Normal | 3296 (860) | 14 (3.2) | 239 (48) | 252 (101) | 293 (157) | 372 (225) | 2.1 (1.2) | 0.29 | 0.15 |
| | Masked | 3436 (1408) | 13.9 (4.4) | 245 (48) | 255 (109) | 294 (155) | 401 (299) | 1.9 (1.2) | 0.32 | 0.16 |

Measures for normal and disappearing text in Experiments (Exp.) 1, 2 and 3. Total sentence reading times (Total RT), average number of fixations (No. fixations), average fixation duration (Fix dur), mean first fixation durations on words (FFD), mean gaze durations on words (Gaze), mean total times on words (TT), total number of regressions (Regressions), probability of skipping a word (Prob. skip), and probability of refixating for those cases in which words were fixated on first pass (Prob. refix). The probability of participants making a single fixation on a word given a first pass fixation is (1 − Prob. refix). Standard deviations in parentheses.

regardless of whether it disappeared or not. The interaction between text and experiment was not reliable, $F\text{s} < 1$.

Average fixation durations were longer when the text and X's disappeared (276 ms) than when they did not (253 ms), $F1(1,22) = 11.47, p < 0.005; F2(1,39) = 9.83$, $p < 0.005$. There was no consistently reliable main effect of experiment and no interaction. [3] Participants made fewer but longer fixations when the stimulus disappeared compared with when it did not, and this effect held regardless of whether they were reading text, or scanning horizontal arrays of X's.

Analyses of the number of regressions showed that participants did not make reliably more regressions when the text or X's disappeared than when the text or X's remained visible throughout a fixation. However, participants made reliably more regressions, $F1(1,22) = 54.16$, $p < 0.001$; $F2(1,39) = 862.19$, $p < 0.001$, when they were reading (1.8) compared with when they were scanning (0.2). The interaction between text and experiment was not reliable.

## 7. Comparative analyses of Experiments 1 and 3

Experiment 3 was a control experiment to confirm that readers were not using iconic memory to read words in the disappearing text condition. The data of Experiments 1 and 3 were compared via 2 (Experiment: removed vs masked) × 2 (Text: normal vs disappearing) ANOVAs, and the results are generally consistent across the two experiments (see Table 2). Comprehension accuracy was similar when text disappeared (89%) compared with when it was presented normally (92%) and the sentence reading times showed no consistent reliable main effect of experiment or text, and no reliable interaction between the two. Thus, there was no processing cost associated with masking the linguistic stimuli after 60 ms compared with making it disappear after 60 ms. While readers made more fixations in Experiment 3 (14) compared to Experiment 1 (13.2), $F1(1,22) = 15.02$, $p = 0.001$; $F2(1,39) = 11.27$, $p < 0.005$ there was no consistent reliable effect of text on the total number of fixations and no consistent reliable interaction.

Average fixation durations were shorter for Experiment 3 (242 ms) than for Experiment 1 (256 ms), $F1(1,22) = 1.12, p > 0.05; F2(1,39) = 15.38, p < 0.001$. Average fixation durations were also shorter for normally presented text (244 ms) than for disappearing and masked text (255 ms), $F1(1,22) = 5.13$, $p < 0.05$; $F2(1,39) = 10.19$, $p < 0.005$, but there was no reliable interaction between text and experiment. We also examined differences in the mean number of regressions made in each experiment and found no effect of text, no consistent effect of experiment, and no consistent reliable interaction between the two.

Word skipping rates did not differ between the experiments and there was no interaction between text and experiment. These results are not surprising given that in both experiments readers carried out exactly the same task—reading for comprehension. Readers made significantly more refixations when reading normal text (0.18) than when reading disappearing or masked text (0.13), $F1(1,22) = 11.08$, $p < 0.005$; $F2(1,39) = 39.95$, $p < 0.001$ suggesting that readers adopt a strategy of decreased likelihood of refixation for text that disappears or is masked after 60 ms during a fixation than for normally presented text. There was no main effect of experiment. However, there was an interaction between experiment and text, $F1(1,22) = 13.49$, $p = 0.001$; $F2(1,39) = 30.80$, $p < 0.001$. Refixation rates were 10% greater for normally presented text than for disappearing text, $t1(1,15) = 5.4$, $p < 0.001$; $t2(1,39) = 9.26$, $p < 0.001$ while the difference between normally presented text and masked text (1%) was not reliable.

There were no differences between the two experiments with respect to fixation time measures for the high/low frequency target words (Table 3), word skipping probability for the short word target words (Table 4), or refixation probability for the long target words (Table 4). Thus, gaze durations were reliably longer for low frequency words (315 ms) than for high frequency words (269 ms), $F1(1,22) = 25.79$, $p < 0.001$; $F2(1,39) = 34.94$, $p < 0.001$, but no other main effects or interactions were reliable.

Finally, the refixation data as a function of frequency clarify the refixation data in general. Readers were more likely to refixate target words that were presented normally (0.17) than those that disappeared or were masked (0.08), $F1(1,22) = 11.75$, $p < 0.005$; $F2(1,39) = 11.82$, $p = 0.001$. Refixations were also more likely for low frequency words (0.17) than for high frequency words (0.08), $F1(1,22) = 17.34$, $p < 0.001$; $F2(1,39) = 22.34$, $p < 0.001$. However, most importantly, these two main effects were qualified by an interaction between text and frequency, $F1(1,22) = 11.75$, $p < 0.005$; $F2(1,39) = 11.82$, $p = 0.001$. Recall that in Experiment 1, there was no reliable influence of frequency on the probability of a refixation on the target word when the text disappeared, but readers were reliably more likely to refixate a low than a high frequency target word when the text was presented normally. Thus, frequency only affected re-

[3] In some of the comparative analyses reported from this point on, there were sometimes effects that were not at all reliable in the participants' analysis but were reliable in the items analysis, or reliable in the participants' analysis but not at all reliable in the items analysis. We adopted a conservative criterion by which we generally only considered effects reliable if they were reliable across both participants and items (exemptions are clearly noted). Thus, the term "not consistently reliable" will be used to refer to those cases in which an effect was not reliable by both participants and items.

Table 3
Local measures: word frequency

| Exp. | Presentation | Frequency | FFD | Gaze | Skip | Refixate |
|---|---|---|---|---|---|---|
| 1 | Normal | High | 258 (70) | 278 (104) | 0.12 | 0.08 |
| | | Low | 271 (94) | 328 (137) | 0.11 | 0.23 |
| | Disappearing | High | 277 (68) | 289 (95) | 0.13 | 0.05 |
| | | Low | 294 (81) | 316 (110) | 0.07 | 0.07 |
| 3 | Normal | High | 244 (95) | 264 (107) | 0.14 | 0.10 |
| | | Low | 258 (73) | 327 (151) | 0.14 | 0.28 |
| | Masked | High | 231 (68) | 246 (72) | 0.12 | 0.09 |
| | | Low | 260 (86) | 288 (109) | 0.11 | 0.10 |

Mean first fixation duration (FFD), gaze duration (Gaze), probability of skipping and probability of refixating for those cases in which the word was fixated on first pass, for high and low frequency words for normal and disappearing text in Experiments (Exp.) 1 and 3. The probability of participants making a single fixation on a word given a first pass fixation is (1 – Prob. refix). Standard deviations in parentheses.

Table 4
Local measures: word length

| Exp. | Presentation | Length | FFD | Gaze | Skip | Refixate |
|---|---|---|---|---|---|---|
| 1 Reading | Normal | Short | 239 (81) | 252 (94) | 0.38 | 0.06 |
| | | Long | 275 (100) | 416 (223) | 0.09 | 0.47 |
| | Disappearing | Short | 295 (124) | 309 (137) | 0.46 | 0.07 |
| | | Long | 286 (100) | 378 (224) | 0.05 | 0.22 |
| 2 Scanning | Normal | Short | 273 (98) | 292 (121) | 0.37 | 0.06 |
| | | Long | 268 (111) | 349 (161) | 0.08 | 0.32 |
| | Disappearing | Short | 272 (151) | 289 (174) | 0.54 | 0.05 |
| | | Long | 296 (109) | 316 (107) | 0.09 | 0.11 |
| 3 Reading | Normal | Short | 255 (104) | 266 (109) | 0.30 | 0.13 |
| | | Long | 251 (97) | 325 (152) | 0.05 | 0.29 |
| | Masked | Short | 245 (111) | 263 (128) | 0.37 | 0.08 |
| | | Long | 270 (94) | 355 (211) | 0.06 | 0.22 |

Measures for normal and disappearing text for short and long words in Experiments (Exp.) 1, 2 and 3. Mean first fixation duration and gaze duration. Standard deviations in parentheses. Probability of skipping on first pass, and probability of making a refixation for those cases in which the word was fixated on first pass, for each condition. The probability of participants making a single fixation on a word given a first pass fixation is (1 – Prob. refix).

fixation probability when the word remained available throughout the time the reader gazed upon it. When it was unavailable for reinspection, frequency had no influence on refixation probability. Clearly, in Experiment 1 refixation probability as modulated by word frequency was itself modulated by the availability of the linguistic information. In Experiment 3, as in Experiment 1, the linguistic information was removed after 60 ms (in this case being replaced by the mask). Note, however, that replacing the word with the mask ensures that a visual object remains in place of the word throughout fixation. Thus, Experiment 3 provides an interesting situation in which we can examine refixation behaviour for high and low frequency words when visual information persists throughout fixation, but useful linguistic information is removed after 60 ms. There were more refixations for low than high frequency words when the word was not masked, $t1(7) = 3.06$, $p < 0.05$; $t2(38) = 3.21$, $p < 0.01$, but there was no difference in refixation rates when the mask replaced the word after 60 ms. Thus, similar patterns of results were obtained in Experiments 1 and 3 and together the findings strongly suggest that linguistic factors affect the probability of refixating when the visual information remains available to be re-sampled.

## 8. General discussion

One of the questions motivating Experiment 1 was whether or not we might be able to obtain a gap effect in reading. That is, if we made the word that the reader was fixating disappear after 60 ms, would fixational offset cause speeded saccade onset latencies, meaning that readers might move their eyes quicker (and hence read faster) than when the text did not disappear. It seemed at least possible that such a gap effect might occur in reading. Prior research (Ishida & Ikeda, 1989; Rayner et al., 1981, 2003) demonstrated that when readers were allowed to fixate text for 50–60 ms prior to either the onset of a visual mask or the text disappearing, they were able to read quite normally. Furthermore, given that simple oculomotor tasks have demonstrated that when a fixation stimulus is removed saccade latencies are shorter than when the fixation stimulus remains, it seemed likely that we might obtain a gap effect in reading.

The results from Experiment 1 demonstrate that the answer to the question of whether or not a gap effect occurred in reading in that experiment is clearly no. We found that readers took no longer to read disappearing text than normal text and their answers to comprehension questions did not differ between normal and disappearing text. However, their eye movement latencies were a little longer, not shorter, for disappearing text than normal text. In addition, the data from Experiment 2 in which participants were required to scan arrays of X's rather than read text also failed to show a gap effect. Although participants spent less time overall scanning X's than reading, there were no differences in overall scanning speed when the X's disappeared compared with when they did not. Thus, in both experiments in which participants were required to either make a series of eye movements to read text or to perform the psychologically less complex task of visually scanning a horizontal array of X's, removing the fixated stimulus after 60 ms did not reduce fixation durations (saccade latencies) and induce a gap effect.

There are at least three possible reasons why we did not obtain a gap effect in our experiments. First, in most studies that investigate the gap effect, participants are simply required to make a single eye movement in any one trial. The most frequently employed paradigm involves the participant fixating a centrally displayed fixation marker. A non-foveal target stimulus then appears and the participant is required to make a saccade to that target as quickly as possible. The centrally presented fixation marker either remains on the screen when the non-foveal target appears, or alternatively, it is extinguished shortly before the target appears. When the fixation marker is extinguished prior to target presentation a gap effect does occur. However, the conditions in our experiment were quite different from this. Participants were required to make a series of successive saccades rather than a single saccade during a single trial.

Second, Dorris and Munoz (1999) suggested that the predictability of the target location may also be related to reduced saccade onset latencies relative to an unpredictable target location. In our studies, one could argue that precise target locations were not predictable, [4] being at different points within words which themselves occurred at different points in the line of text or array of X's. Additionally, even the direction of the saccade (left or right) could not be known for certain for any particular fixation. Thus, the fact that in our study participants made sequences of successive saccades to target locations that were not highly predictable may have contributed to our failure to obtain a gap effect during reading.

A third possible reason why we did not obtain a gap effect is that in our experiments there was no non-foveal target onset. Instead, other than the fixated word disappearing, the sentence remained constant prior to and during the saccade. It seems possible that in studies that have successfully demonstrated a gap effect, the onset of the non-foveal target stimulus seems likely to be an aspect of the paradigm that contributes to the emergence of the effect. A commonality across all of these possible explanations regarding the lack of a gap effect in the present experiment is that it appears that fixational offset alone is insufficient to induce a gap effect.

What is clear, however, from Experiments 1 and 2 together is that the reason we failed to find a gap effect during reading was not due to participants being required to carry out linguistic as well as visual processing. The lack of a gap effect when participants were required to simply perform visual processing (scanning arrays of X's) rather than visual as well as language processing (reading) allows us to rule out the possibility that the failure to find a gap effect was due to additional cognitive processing associated with language comprehension.

Although we did not find evidence for a gap effect in Experiments 1 and 2, the data from both experiments along with the data from Experiment 3 provide significant insight concerning a number of aspects of oculomotor control during reading, and in particular, factors that influence when we move our eyes during reading. While we found that overall reading times for the sentences were the same under normal and disappearing text conditions in Experiment 1, there was a tradeoff between the duration of first fixations and the probability of refixating words. Consequently the global analyses show that readers made longer fixation durations but slightly fewer fixations when reading disappearing text in comparison to normal text. There are two possible explanations for the longer average fixation durations when reading disappearing text. First, the brief presentation of text may have produced saccadic inhibition as reported by Reingold and Stampe (2000, 2002, in press). They demonstrated that a sudden irrelevant flash or a sudden change in the text characteristics can cause the onset of the next fixation to be delayed. The sudden disappearance of the text in our experiment may likewise cause the onset of the next fixation to be slightly delayed. The second possible explanation is that readers reduce the number of refixations when the text disappeared because refixations do not provide visual

[4] Of course, it is the case that most saccades move the eyes rightward in the text. Thus, one could argue that the next target location is generally predictable as the word to the right of fixation. For the general argument presented here, however, the point is simply that the exact location for a saccade, in terms of a specific location in a target word, may not be a priori highly predictable.

and linguistic information at fixation. In order that the eyes only move when visual and linguistic processing of the fixated word is complete, such a strategy must be accompanied by longer fixations.

One of the most striking findings from both Experiments 1 and 3, particularly the local analyses, is that the cognitive processes associated with understanding the text are a critical determinant of when the eyes move. That is, even though the target word had either disappeared or been masked, readers still looked longer at low frequency words than high frequency words. That is, readers continued to fixate a blank (or masked) portion of the sentence after the word had disappeared for a time that was proportional to the frequency of the word that had previously been there. Thus, the ease or difficulty associated with linguistically processing a word influenced when the eyes moved on. This finding is consistent with models of eye movement control in reading (Engbert, Longtin, & Kliegl, 2002; Morrison, 1984; Reichle, Pollatsek, Fisher, & Rayner, 1998; Reichle, Rayner, & Pollatsek, 1999, 2003; Reilly & Radach, 2003) which posit that cognitive and lexical processing determines when the eyes move in reading. It is also inconsistent with models (O'Regan, 1992; Yang & McConkie, 2001) in which lexical processing is only incidentally related to eye movement control.

Another important point to note is that the effects that we observed in Experiment 1 were not due to processing carried out on an iconic memory trace of the word after it had disappeared. In Experiment 3 the disappearing words were backward masked with a string of X's to prevent storage of the visual word form in some form of iconic memory buffer and we obtained very similar effects across the two experiments. Thus, it seems unlikely that the effects observed in Experiment 1 are caused by processing of iconic traces of the words after they had disappeared.

A final interesting contrast between two of the experiments is that the time to read sentences in their entirety was substantially longer in Experiment 1 than the time to scan the arrays of X's in Experiment 2. It seems likely that the additional time taken to read sentences compared with scanning X's is associated with the extra linguistic processes involved in reading compared with simply visually scanning non-linguistic stimuli. This finding can be contrasted with data from studies by Vitu, O'Regan, Inhoff, and Topolski (1995) and Rayner and Fischer (1996). In both of these studies participants were instructed to move their eyes along horizontal arrays of groups of Z's as if they were reading. In both studies "reading times" were longer for Z-strings than for normal text (the opposite result to that obtained in our study). The reason for this inconsistency appears to be differences in the instructions participants were given. In our Experiment 2, participants were simply told to scan along the horizontal array of X's and press a button when they had reached the right end of the array. In particular we were very careful not to indicate that they should try to behave as though they were reading. Thus, requesting that participants attempt to mimic reading behaviour in the Vitu et al. and Rayner and Fischer studies apparently led them to spend more time "processing" meaningless text than would have been the case had they been required to simply scan the Z's (though the exact nature of the "processes" they are undertaking during this additional time is not clear).

## 9. Conclusions

The data from Experiments 1 and 2 indicate that there is not a gap effect during reading of text or scanning of horizontal strings of X's. The data from Experiment 1 also indicate that the frequency of a word affects how long readers remain fixating that word (even if foveal visual stimulation is terminated). The data from Experiment 3 indicate that these effects are not due to processing of iconic memory traces. The comparative analyses between experiments indicate that the probability of refixating a word is influenced both by the continued presence of a visual object and also by the continued presence of linguistic information throughout fixation. Finally, the most striking result from the experiments is that readers continue fixating a low frequency word longer than a high frequency word even when the word is no longer there (having either disappeared or been masked).


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