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Eye movements when reading disappearing text: The importance of the word to the right of fixation

Keith Rayner [a,*], Simon P. Liversedge [b], Sarah J. White [b]

[a] Department of Psychology, University of Massachusetts, Amherst, MA 01003, USA
[b] Department of Psychology, University of Durham, Durham DH1 3LE, UK

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Abstract

In a series of experiments, the currently fixated word (word *n*) and/or the word to the right of fixation (word $n+1$) either disappeared or was masked during readers' eye fixations. Consistent with prior research, when only word *n* disappeared or was masked, there was little disruption to reading. However, when word $n+1$ either disappeared or was masked (either at the onset of fixation on word *n* or after 60 ms), there was considerable disruption to reading. Independent of whether word *n* and/or word $n+1$ disappeared or was masked, there were robust frequency effects on the fixation on word *n*. These results not only confirm the robust influence of cognitive/linguistic processing on fixation times in reading, but also again confirm the importance of preprocessing the word to the right of fixation for fluent reading.

Keywords: Eye movements; Reading; Saccades; Fixation durations; Disappearing text

1. Introduction

The visual information necessary for reading is obtained during eye fixations that typically last about 200–250 ms (Liversedge & Findlay, 2000; Rayner, 1998; Starr & Rayner, 2001). Between the fixations, when the eyes actually move from one location to another in the text, vision is suppressed such that no useful information is obtained (Wolverton & Zola, 1983). Interestingly, it is the case that only 50–60 ms is needed for the input of the visual information that is necessary for reading to proceed quite smoothly. Rayner, Inhoff, Morrison, Slowiaczek, and Bertera (1989) first demonstrated that if readers see text for only 50–60 ms of each fixation before a masking pattern appears, reading is quite normal (see also Ishida & Ikeda, 1989). More recently, we (Liversedge et al., 2004; Rayner, Liversedge, White, & Vergilino-Perez, 2003) also found that if readers see a word for 60 ms before it disappears, reading proceeds unimpaired.[1]

Perhaps the most interesting finding in these recent disappearing text studies (Liversedge et al., 2004; Rayner et al., 2003) is that fixation time on a word was influenced by the word's frequency even after it had disappeared. It is well known that under normal reading conditions, readers look at low frequency words longer than high frequency words (Inhoff & Rayner, 1986; Rayner & Duffy, 1986). That the frequency effect

* Corresponding author. Fax: +1 413 545 0996.
E-mail address: rayner@psych.umass.edu (K. Rayner).

[1] This does not mean that processing of a word is completed in 60 ms. Rather, it means that 60 ms is sufficient to encode the visual stimulus. Given that it takes approximately 150 ms to program a new saccade in reading (Rayner, Slowiaczek, Clifton, & Bertera, 1983), during the ensuing time after the initial 60 ms, readers are also presumably engaged in processing the encoded information at higher levels.

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maintains even when the fixated word has disappeared after 60 ms provides strong evidence that on-going cognitive processes strongly influence when the eyes move: despite the word no longer being there, how long the eyes remain fixated on that location is determined by how frequent the word is. This finding is quite consistent with models of eye movement control in reading, such as the E-Z Reader model (Reichle, Pollatsek, Fisher, & Rayner, 1998; Reichle, Rayner, & Pollatsek, 1999, 2003), which posit that cognitive and lexical processing determines when the eyes move in reading. It is also inconsistent with models in which lexical processing is only incidentally related to eye movement control (O'Regan, 1992; Yang & McConkie, 2001, 2004).

In the experiments reported here, we sought to examine whether reading still remains normal under more extreme disappearing text conditions. Rayner et al. (1989) previously demonstrated that when the text was masked earlier in a fixation than 50 ms, reading was disrupted. Here, we further examined the limits of processing when reading disappearing text by having not only the fixated word disappear after 60 ms, but also the word to the right of fixation. In the experiments, each word in a sentence disappeared or was masked when either it or the word to the left of it was fixated. For the most part, we were interested in the disruption caused by the word to the right of fixation (word $n + 1$) either disappearing or being masked. Whereas, it is obviously the case that the fixated word is very important in reading (since the frequency of the fixated word strongly influences when the eyes move off of a word), the word to the right of fixation is also critical. Given that the perceptual span (or region of effective vision) in reading extends from the beginning of the currently fixated word (or 3–4 letters to the left of fixation generally) to 14–15 letters to the right of fixation (McConkie & Rayner, 1975; Rayner & Bertera, 1979; see Rayner, 1998 for a complete review), attention (followed by a saccade) generally moves to the right of fixation (Henderson & Ferreira, 1990; Morrison, 1984), except in those cases where a regressive saccade is programmed. Indeed, we know that readers process the word to the right of fixation since they typically obtain preview benefit effects (see Rayner, 1998). For example, if the word to the right of fixation is masked or altered in some way (i.e., some of the letters of the word are replaced by other letters), the next fixation will be prolonged by about 30–50 ms (Blanchard, Pollatsek, & Rayner, 1989; Hyönä, Bertram, & Pollatsek, 2004; Rayner, Well, Pollatsek, & Bertera, 1982). Given this highly reliable preview benefit effect, we suspected that if the word to the right of fixation also disappeared after 60 ms, then reading in the disappearing text condition would be disrupted (compared to both normal reading and the case in which only the fixated word disappeared).

Data from three main experiments are reported. In all of the experiments we included a word frequency manipulation such that selected target words in the sentence were either high or low frequency words. In Experiment 1a, participants read sentences presented normally or under disappearing text conditions in which both the fixated word and the word to the right of fixation disappeared after 60 ms. Performance when two words disappeared was compared to performance when reading was normal (i.e., no disappearing text) and also to when only the fixated word disappeared (Control experiment). In Experiment 1b, the fixated word disappeared and the word to the right was masked after 60 ms. The mask provided visual information about the size of the word, but no linguistic information. In our prior disappearing text experiments (Liversedge et al., 2004), we compared a condition in which the fixated word disappeared to a condition in which the fixated word was masked, with both presentation conditions producing similar results. In a similar way, in these experiments we compared effects obtained when word $n + 1$ disappeared with those obtained when word $n + 1$ was masked. Using this masking procedure allowed us to determine the extent to which the effects that we obtained were due to the removal of visual aspects of word $n + 1$ (word size and shape), or alternatively, the removal of the linguistic characteristics of word $n + 1$ (orthographic properties of the word).

In Experiments 2a and 2b we compared the degree of disruption caused by word n disappearing after 60 ms (Control experiment) with word $n + 1$ disappearing (Experiment 2a) or being masked (Experiment 2b) at the onset of the fixation on word n. Liversedge et al. (2004) and Rayner et al. (2003) showed that the disappearance of word n does not disrupt reading. Experiments 2a and 2b tested whether the disappearance (or masking) of word $n + 1$ disrupts reading compared to both normal reading conditions and conditions under which word n disappears (Control experiment). Similar to the comparison of Experiments 1a and 1b, if only the visual word length characteristics of word $n + 1$ are preprocessed then there should be disruption only when word $n + 1$ disappears (Experiment 2a) but if the linguistic characteristics of word $n + 1$ are preprocessed then there should be disruption when word $n + 1$ disappears or when it is masked (Experiment 2b). Finally, in Experiments 3a and 3b, word $n + 1$ either disappeared (Experiment 3a) or was masked (Experiment 3b) 60 ms after fixation onset on word n. These experiments allowed us to examine the exclusive influence of disruption to word $n + 1$ when it was available to be processed for the first 60 ms of the fixation on word n and when there was no concurrent disruption to word n.

2. Method

2.1. Participants

Fifty-six members of the University of Durham community participated in the experiments. All were native English speakers with normal or corrected to normal vision. They were paid to participate, and all were naïve with respect to the purpose of the experiment. No participant took part in more than one experiment. In Experiment 1a, eight participants read when word n and word $n+1$ disappeared after 60 ms; in Experiment 1b, eight participants read sentences when word n disappeared and word $n+1$ was masked after 60 ms; in Experiment 2a, eight participants read when word $n+1$ disappeared at the onset of each new fixation; in Experiment 2b, eight participants read when word $n+1$ was masked at the onset of each new fixation. In Experiment 3a, another group of eight participants read when only word $n+1$ disappeared 60 ms after the onset of a fixation on word n. In Experiment 3b, eight participants read when word $n+1$ was masked 60 ms after the onset of the fixation. Finally, eight participants read in the original disappearing text condition (identical to the experiments in Liversedge et al., 2004) in which only the fixated word disappeared after 60 ms. This latter group of participants serve as a control group and each of the other groups of participants' performance was compared to their performance. In addition to reading under the experimental conditions (in which text disappeared or was masked), each group of participants read text under normal reading conditions (as a further baseline comparison).

2.2. Materials and design

The same 40 sentences were read by all of the participants (and were the same as those read by participants in Liversedge et al.). Each sentence contained a critical high or low frequency target word (which was always six letters long). The sentences were presented normally on half the trials while on the other half of the trials a word (or two words) disappeared (or were masked by X's) at certain points relative to the onset of the fixation on the word. The words only reappeared once a saccade was made to another word (either to the left via a regression or to the right of the currently fixated word via a forward saccade). If readers refixated a word (i.e., made a second fixation on the word prior to fixating a different word), the word (or words) that had disappeared (or was/were masked) did not reappear until a saccade was made to another word. With respect to the disappearing text conditions, it is important to note that Rayner et al. (2003) carried out a "shutter test" with the current apparatus to confirm that phosphor persistence did not enable participants to view a fading image of the words after they disappeared from the monitor. Table 1 shows examples of each of the conditions.

Each sentence occupied a single line no longer than 80 letters. Two lists of 50 sentences were constructed and in each experiment half of the participants were randomly assigned to each list. Each list contained 40 experimental sentences; half included a frequent critical word and half an infrequent word. The critical high and low frequency words were embedded within the same sentence frames and the two versions of each of the forty experimental sentences were counterbalanced across the two lists of sentences. Word frequencies were calculated using the CELEX database (Baayen, Piepenbrock, & Gulikers, 1995). The high frequency words were significantly higher frequency ($M = 105$, $SD = 162$) than the low frequency words ($M = 1$, $SD = 2$), $t(39) = 4.06$, $p < 0.001$. The sentences were presented in a fixed random order, but in two blocks with 20 experimental sentences in each block. In each experiment, one block was presented in normal text and one block was presented in disappearing text or masked text format (depending on the experiment). The order of blocks was counterbalanced across participants. Five filler sentences were presented at the beginning of each block and 16 comprehension questions appeared scattered throughout the blocks.

2.3. Apparatus

Eye movements were sampled every millisecond by a Fourward Technologies Dual Purkinje Generation 5.5 eye-tracker with spatial resolution of less than 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; five letters subtended 1° of visual angle. The monitor had a P22 phosphor with decay rate to 0 in less than 1 ms. The monitor and the eye-tracker were interfaced with a Phillips Pentium III PC that controlled the experiment.

2.4. Procedure

Participants were instructed to read the sentences 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. The initial calibration of the eye-tracker lasted about 5 min and the calibration accuracy was checked after every trial. An experiment lasted about 30 min. Readers were able to answer the comprehension questions quite well (overall accuracy = 90% across the experiments).

Table 1
Examples of disappearing text showing what is present on the video monitor at the beginning of a fixation and after 60 ms of the fixation on word *n*

Exp.	Time	Word *n*	Word *n* + 1	Example
Control	Beginning of fixation	Present	Present	He found the secret manuscript inside the little
Control	After 60 ms	Disappear	Present	He found the manuscript inside the little
1a	Beginning of fixation	Present	Present	He found the secret manuscript inside the little
1a	After 60 ms	Disappear	Disappear	He found the inside the little
1b	Beginning of fixation	Present	Present	He found the secret manuscript inside the little
1b	After 60 ms	Disappear	Masked	He found the XXXXXXXXXX inside the little
2a	Beginning of fixation	Present	Disappear	He found the secret inside the little
2a	After 60 ms	Present	Disappear	He found the secret inside the little
2b	Beginning of fixation	Present	Masked	He found the secret XXXXXXXXXX inside the little
2b	After 60 ms	Present	Masked	He found the secret XXXXXXXXXX inside the little
3a	Beginning of fixation	Present	Present	He found the secret manuscript inside the little
3a	After 60 ms	Present	Disappear	He found the secret inside the little
3b	Beginning of fixation	Present	Present	He found the secret manuscript inside the little
3b	After 60 ms	Present	Masked	He found the secret XXXXXXXXXX inside the little

In the example the reader fixates on *secret*. After a word disappears or is masked, it is not presented again until the reader makes an eye movement to a new word.

3. Results and discussion

For each of the experiments, global measures of sentence reading time, number of fixations, average fixation duration, number of regressions, and the probability of a refixation (making another fixation on the word before moving to a new word) are reported. In addition, local measures of processing with respect to the critical target words (high or low frequency) are reported. These include the 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), and the total fixation time (the sum of all fixations on a word including regressions to the word). For first fixation, gaze duration, and total fixation time measures, fixations shorter than 80 ms were excluded from the analyses. First fixation durations longer than 1200 ms were also excluded. Analyses are based on variability due to participants ($F1$, $t1$) and items ($F2$, $t2$). Following Liversedge et al. (2004), we adopted a conservative criterion by which we only considered effects reliable if they were significant across both participants and items (exceptions are clearly noted below).

Table 2 shows the global reading time measures across the main experiments reported here. Specifically, Table 2 shows sentence reading time, number of fixations, mean fixation duration, number of regressions, and probability of making a refixation in the normal or disappearing/masking conditions. Examination of Table 2 reveals four striking effects. First, across all of the experiments, the normal reading condition differs very little across experiments and whatever variability is present is presumably due to the between participants

Table 2
Global measures

Exp.	Presentation	Total RT	NFix	FixDur	NReg	Prob. Ref.
Control	Normal	3367 (790)	14 (3)	249 (27)	1.5 (1.1)	0.22
	Disappear	3359 (1053)	13 (4)	271 (47)	1.7 (1.3)	0.09
1a	Normal	3208 (1097)	13 (4)	246 (36)	1.7 (1.6)	0.18
	Disappear	4361 (1421)	17 (6)	256 (52)	4.0 (2.0)	0.12
1b	Normal	3551 (1125)	15 (4)	237 (48)	2.9 (1.7)	0.20
	Masked	5203 (1883)	20 (6)	255 (53)	4.6 (2.4)	0.15
2a	Normal	3449 (1224)	14 (5)	246 (39)	2.2 (1.6)	0.15
	Disappear	4045 (1324)	15 (4)	268 (40)	2.6 (1.4)	0.23
2b	Normal	3256 (1078)	14 (3)	238 (44)	1.9 (1.3)	0.19
	Masked	4337 (1187)	16 (5)	286 (65)	1.8 (1.3)	0.26
3a	Normal	3149 (1065)	15 (4)	213 (32)	2.2 (1.3)	0.15
	Disappear	3953 (1371)	16 (5)	245 (44)	2.8 (1.4)	0.20
3b	Normal	3256 (1099)	14 (5)	241 (36)	1.6 (1.5)	0.17
	Masked	4209 (1110)	16 (4)	276 (50)	2.3 (1.4)	0.23

Total RT, total sentence reading time (in ms); Nfix, number of fixations; FixDur, average fixation duration; Nreg, number of regressions; Prob. Ref., probability of an immediate refixation on word *n*. Standard deviations are in parentheses.

manipulation (since different participants took part in the different experiments). Thus, the mean sentence reading time for the normal reading conditions (computed from Experiments 1–3) was 3312 ms (and this value is very similar to the reading time of 3367 ms for the control participants in the normal reading condition) suggesting that the participants across the different experiments read at similar rates and are fairly typical readers. Second, the only disappearing/masking condition that yields a mean sentence reading time (3359 ms) that is comparable to the normal reading condition is for the control participants. This is basically a replication of the results reported by Liversedge et al. (2004) and Rayner et al. (2003): sentence reading was not hindered when only the fixated word disappeared after 60 ms (note also, Liversedge et al. also showed that whether the fixated word disappeared or was masked made no difference). Because the data for the control participants are identical to those reported by Liversedge et al. for the other variables, we will not discuss the control comparison between normal and disappearing text (with only the fixated word disappearing) further. We will, however, use the Control experiment to compare with the other experiments. Third, when the word to the right disappeared or was masked, reading was considerably disrupted and there appeared to be more disruption when it was masked than when it disappeared. Finally, disruption to both word n and word $n+1$ appears to be more serious than disruption to just word $n+1$.

4. Experiments 1a and 1b: global measures

In Experiment 1a, reading was either normal or word n and word $n+1$ both disappeared after 60 ms. In Experiment 1b, reading was either normal or word n and word $n+1$ were disrupted after 60 ms (word n disappeared and word $n+1$ was masked). The data were analyzed via a 2 (reading condition: normal vs disrupted) × 3 (type of disruption: only word n disappeared, word n and word $n+1$ both disappeared, or word n disappeared and word $n+1$ masked) analysis of variance (ANOVA). The first variable was manipulated within participants and the second was varied between participants.

4.1. Sentence reading time

Reading was faster for the normal reading condition than the disrupted conditions, $F1(1,21) = 38.7$, $p < 0.001$, $F2(1,39) = 98.68$, $p < 0.001$ and there were differences due to type of disruption that were apparent in the items analysis, $F1(2,21) = 2.38$, $p = 0.117$, $F2(2,78) = 95.95$, $p < 0.001$. However, the most important result was the significant interaction, $F1(2,21) = 10.8$, $p < 0.01$, $F2(2,78) = 32.47$, $p < 0.001$. Post hoc t tests clarified the nature of the interaction. First, there was no reliable difference between the three normal reading conditions. Second, there were differences between the normal and disrupted conditions when two words were disrupted. When both words disappeared, reading times were much longer than in the normal condition, $t1(7) = 6.27$, $p < 0.001$, $t2(39) = 10.94$, $p < 0.001$. Likewise, when word n disappeared and word $n+1$ was masked, reading was much longer than in the normal condition, $t1(7) = 4.39$, $p < .01$, $t2(39) = 7.71$, $p < 0.001$. Third, reading times were longer when both words were disrupted than when only word n disappeared: $t1(14) = 2.11$, $p = .054$, $t2(39) = 8.6$, $p < 0.001$ when the word to the right disappeared, and $t1(14) = 3.07$, $p < 0.01$, $t2(39) = 14.45$, $p < 0.001$ when the word to the right was masked.

Finally, a comparison of word $n+1$ disappearing or being masked was carried out via a 2 (reading condition: normal vs disrupted) × 2 (type of disruption: $n+1$ disappeared vs $n+1$ masked) ANOVA. Reading was faster in the normal condition than the disrupted conditions, $F1(1,14) = 44.74$, $p < 0.001$, $F2(1,39) = 248.75$, $p < 0.001$. There was a significant main effect of type of disruption across items, although not participants, $F1(1,14) = 1.23$, $p = 0.286$, $F2(1,39) = 33.56$, $p < 0.001$. While there was no statistically reliable interaction, $F1(1,14) = 1.45$, $p = 0.248$ and $F2(1,39) = 3.33$, $p = 0.076$, reading times were numerically longer under the masked than the disappearing conditions.

4.2. Number of fixations and fixation durations

The data pattern for number of fixations closely mimicked the reading time data (see Table 2) with main effects of reading condition, $F1(1,2{\cdot}1) = 36.62$, $p < 0.001$, $F2(1,39) = 52.75$, $p < 0.001$, and type of disruption, $F1(2,21) = 4.25$, $p < 0.05$, $F2(2,78) = 107.83$, $p < 0.001$. More importantly, the interaction was significant, $F1(2,21) = 17.99$, $p < 0.001$, $F2(2,78) = 29.27$, $p < 0.001$, with the pattern generally the same as the reading times.

The average fixation duration data (see Table 2) were somewhat different from the number of fixations in that the interaction did not approach significance (Fs < 1.1). The only reliable effect across the experiments/conditions was that fixations were longer when the text disappeared/was masked than when it was normal, $F1(1,21) = 12.05$, $p < 0.01$, $F2(1,39) = 47.64$, $p < 0.001$. A similar effect was also reported by Liversedge et al. (2004).

4.3. Regressions and refixations

For regressions (see Table 2), the main effects and interaction were significant across participants and items (all ps < 0.05). Thus, there were more regressions when text disappeared or was masked than when it was normal, two words disappearing (or being masked) resulted in more regressions than one word disappearing. Reading normal text resulted in more refixations (see Table 2) than reading disappearing or masked text ($ps < 0.001$). This latter result replicates Liversedge et al. (2004) and Rayner et al. (2003).

5. Experiments 1a and 1b: local measures[2]

5.1. Frequency effects

Table 3 shows the first fixation duration, gaze duration, and total reading time measures across the experiments. We carried out 2(reading condition: normal vs disrupted) × 3(type of disruption: only word n disappeared, word n and word $n+1$ both disappeared, or word n disappeared and word $n+1$ was masked) × 2(frequency: high vs low frequency target word) ANOVAs on the different fixation measures.[3] For first fixation duration and gaze duration, the only reliable effect was that of frequency: first fixation duration was 260 ms for high frequency words and 286 ms for low frequency words, $F1(1,21) = 17.33$, $p < 0.001$, $F2(1,20) = 7.14$, $p < .05$; gaze duration was 289 ms for high frequency words and 339 ms for low frequency words, $F1(1,21) = 12.94$, $p < 0.01$, $F2\ (1,21) = 8.41$, $p < 0.01$. Thus, as observed by Liversedge et al. (2004) and Rayner et al. (2003), the frequency effect was maintained independent of the type of disruption.

For the sake of completeness, we have presented the total fixation time data in Table 3. The frequency effect was significant ($p < 0.001$). However, in contrast to the first fixation duration and gaze duration data, the total fixation time data were more complex. We will not discuss these data further since they are of less interest than the first fixation duration and gaze duration data because they do not reflect initial processing activity during reading (since regressions back to the target word are included in the measure).

6. Experiments 1a and 1b: summary

When word n disappeared and word $n+1$ also either disappeared or was masked after 60 ms, sentence reading times were longer, there were more fixations, and more regressions compared to when only word n disappeared. These results are in line with previous studies which show that word $n+1$ is preprocessed during reading (see Rayner, 1998).

The probability of making a refixation was reduced when word n disappeared compared to the normal presentation condition. As explained by Liversedge et al. (2004), this suggests that first pass refixation

Table 3
Local measures

Exp	Presentation	Frequency	FFD	Gaze	Total time
Control	Normal	High	260 (70)	295 (124)	357 (170)
		Low	283 (100)	325 (122)	483 (250)
		FE	23	30	126
	Disappear	High	277 (54)	288 (81)	356 (172)
		Low	300 (79)	329 (118)	592 (381)
		FE	23	41	236
1a	Normal	High	255 (65)	292 (102)	337 (163)
		Low	304 (142)	373 (199)	534 (484)
		FE	49	81	197
	Disappear	High	262 (112)	297 (144)	491 (270)
		Low	272 (122)	317 (216)	673 (476)
		FE	10	20	182
1b	Normal	High	260 (98)	293 (106)	434 (218)
		Low	285 (113)	335 (167)	521 (277)
		FE	25	42	87
	Masked	High	248 (102)	268 (110)	681 (383)
		Low	271 (116)	354 (311)	859 (572)
		FE	23	86	178
2a	Normal	High	264 (82)	298 (113)	384 (217)
		Low	278 (97)	336 (133)	572 (304)
		FE	14	38	188
	Disappear	High	309 (122)	380 (194)	511 (334)
		Low	315 (151)	447 (329)	617 (381)
		FE	6	67	106
2b	Normal	High	253 (69)	283 (95)	352 (187)
		Low	266 (89)	316 (129)	437 (229)
		FE	13	33	85
	Masked	High	305 (102)	362 (134)	453 (179)
		Low	313 (120)	442 (226)	562 (269)
		FE	8	80	109
3a	Normal	High	221 (53)	245 (105)	373 (210)
		Low	233 (74)	276 (148)	476 (304)
		FE	12	31	103
	Disappear	High	254 (99)	301 (133)	443 (246)
		Low	283 (114)	355 (177)	574 (253)
		FE	29	54	131
3b	Normal	High	252 (64)	281 (94)	374 (210)
		Low	279 (91)	320 (148)	518 (310)
		FE	27	39	144
	Masked	High	289 (103)	349 (167)	471 (231)
		Low	328 (120)	429 (232)	603 (257)
		FE	39	80	132

First fixation duration, gaze duration, and total fixation time (all in ms) on high and low frequency target words. *FE*, frequency effect. Standard deviations are in parentheses.

[2] All the local measures analyses reported in this article focus on the high/low frequency target words and the fixation time on those words. However, it is important to realize that the target word may also be regarded as word $n+1$ on the fixation on the prior word.

[3] For the local analyses of word frequency for Experiments 1a and 1b, not all items produced data for each of the conditions. Consequently the items analyses for the first fixation duration measures are based on 21 items, and those for the gaze duration measures are based on 22 items.

probabilities are determined to a substantial extent by the availability of visual and/or linguistic information. That is, in the conditions in which word n disappeared no extra information could be obtained when it was refixated (because word n does not reappear until the eyes move away from the word). Also, all of the disappearing conditions in the present experiment produced longer average fixation durations than the normal presentation condition. Liversedge et al. suggested that the longer average fixation durations when word n disappeared might be due to a compensation strategy occurring as a consequence of the reduced refixation possibilities. It is quite likely that a similar trade off also occurred in Experiments 1a and 1b, however the reduced preview of word $n+1$ (caused by word $n+1$ disappearing or being masked) may also have contributed to lengthened average fixation durations.

The first fixation duration and gaze duration data provide clear confirmation that frequency effects were evident not only when the fixated word disappeared or was masked after 60 ms (Liversedge et al., 2004; Rayner et al., 2003), but also when both the fixated word and the word to the right of fixation disappeared or was masked after 60 ms. These results provide further support to the substantial body of evidence indicating that cognitive processes are very much involved in the decision of when to move the eyes (see Rayner, 1998; Rayner et al., 2003).

7. Experiments 2a and 2b: global measures

In Experiment 2a, the word to the right of fixation (word $n+1$) disappeared as soon as the reader fixated word n; in Experiment 2b, word $n+1$ was masked as soon as the reader fixated word n. This situation is obviously different from Experiments 1a and 1b where word n and word $n+1$ disappeared (or word $n+1$ was masked) after 60 ms. We decided to make the disappearance of word $n+1$ coincident with the onset of fixation on word n because we were concerned that the sudden offset of the word to the right of fixation might be disruptive at a point after fixation onset. Our primary goal was to determine what cost is associated with word $n+1$ being unavailable for preprocessing, rather than disruption due to visual changes in non foveal locations. We did not want noise added from a mid-fixation sudden offset. However, in Experiments 3a and 3b (see below and Section 12.2), we did have word $n+1$ disappear after 60 ms to objectively deal with any disruptive effect it might have.

7.1. Sentence reading time

The sentence reading time results were very similar to Experiments 1a and 1b (see Table 2). Reading was faster for the normal reading condition than the disrupted conditions, $F1(1,21) = 25.32$, $p < 0.001$, $F2(1,39) = 63.72$, $p < 0.001$ and there were differences due to type of disruption that were apparent in the items analysis, $F1 < 1$, $F2(2,78) = 76.84$, $p < 0.001$. However, the most important result was again the significant interaction, $F1(2,21) = 8.24$, $p < 0.01$, $F2(2,78) = 12.86$, $p < 0.001$. Post hoc t tests clarified the nature of the interaction. First, there were no reliable differences between the three normal reading conditions. Second, there were differences between the normal and disrupted conditions when word $n+1$ was disrupted. When word $n+1$ disappeared, reading was longer than in the normal condition, $t1(7) = 2.84$, $p < 0.05$, $t2(39) = 2.94$, $p < 0.01$. Likewise, when word $n+1$ was masked, reading was longer than in the normal condition, $t1(7) = 5.4$, $p < 0.01$, $t2(39) = 10.94$, $p < 0.001$. Third, reading times were longer when word $n+1$ was disrupted than when only word n disappeared: $t1(14) = 1.41$, $p = .18$, $t2(39) = 5.23$, $p < 0.001$, when word $n+1$ disappeared immediately, and $t1(14) = 2.49$, $p < 0.05$, $t2(39) = 9.23$, $p < 0.001$ when word $n+1$ was masked immediately.

It appears that while making the fixated word disappear did not induce processing difficulty, making the word to the right of fixation disappear did. Thus, we have the interesting finding that making a word that a reader is looking at disappear does not cause reading difficulty, but making a word disappear that is not yet being looked at does cause such difficulty.

Finally, a comparison for when word $n+1$ disappeared or was masked was carried out via a 2(reading condition: normal vs disrupted) × 2(type of disruption: $n+1$ disappeared vs $n=1$ masked) ANOVA. There was a main effect of reading condition, $F1(1,14) = 33.69$, $p < 0.001$, $F2(1,39) = 37.59$, $p < 0.001$, and a significant interaction across items, $F2(1,39) = 9.11$, $p < 0.01$, but not participants, $F1(1,14) = 3.02$, $p = 0.104$. Similar to the comparisons for Experiments 1a and 1b, there were numerically longer reading times when word $n+1$ was masked (Experiment 2b) than when word $n+1$ disappeared (Experiment 2a).

7.2. Number of fixations and fixation durations

The data pattern for number of fixations again mimicked the reading time data (see Table 2). However, the only effect that was significant (or approached significance) in both the participants and items analyses was the interaction, $F1(2,21) = 3.16$, $p = 0.063$, $F2(2,78) = 9.22$, $p < 0.001$.

For the fixation duration data (see Table 2), the most obvious effect was that fixations were longer when word $n+1$ disappeared/was masked than when it was normal, $F1(1,21) = 41.77$, $p < 0.001$, $F2(1,39) = 206.65$, $p < 0.001$. The interaction was significant by items and marginal by participants, $F1(2,21) = 3.38$, $p = 0.054$,

$F2(2,78) = 13.38$, $p < 0.001$. The means show that fixations were approximately the same under the two normal conditions, and that fixations were differentially longer when words were masked than when they disappeared.

7.3. Regressions and refixations

For regressions (see Table 2), the data are less clear. Regressions occurred to a similar degree in the normal and masked conditions of Experiment 2b. For Experiment 2a, more regressions occurred under disappearing than normal conditions. Overall, there was a main effect of reading condition with most regressions occurring when word $n+1$ disappeared compared to normal reading, though the effect was only reliable by items, $F1(1,21) = 2.34$, $p = 0.121$, $F2(1,39) = 53.85$, $p < 0.001$.

The pattern of data with respect to the probability of refixating was very different in Experiments 2a and 2b (compared to the Control and Experiments 1a and 1b). Specifically, there were more refixations on word n when word $n+1$ disappeared or was masked than when the sentence was presented normally (ps < 0.05). By contrast, in the Control experiment and Experiments 1a and 1b, readers were much more likely to refixate a word in the normal reading condition than the disappearing/masking conditions.

8. Experiments 2a and 2b: local measures

8.1. Frequency effects

Table 3 shows the first fixation duration, gaze duration, and total reading time measures. We carried out 2(reading condition: normal vs disrupted) × 3(type of disruption: only word n disappeared, word $n+1$ disappeared, or word $n+1$ was masked) × 2(frequency: high vs low frequency target word) ANOVAs on the different fixation measures.[4] As with Experiments 1a and 1b, there were effects of frequency with low frequency words receiving longer first fixations and gaze durations than high frequency words. First fixation duration was 278 ms for high frequency words and 293 ms for low frequency words, $F1(1,21) = 3.87$, $p = 0.063$, $F2(1,30) = 8.07$, $p < 0.01$; gaze duration was 318 ms for high frequency words and 366 ms for low frequency words, $F1(1,21) = 8.88$, $p < .01$, $F2(1,31) = 23.56$, $p < 0.001$.

Unlike Experiments 1a and 1b, there were significant effects due to reading condition with first fixations being longer when the text was disrupted (303 ms) than when it was normal (267 ms), $F1(1,21) = 18.96$, $p < 0.001$, $F2(1,30) = 19.87$, $p < 0.001$, and gaze durations likewise showing a similar disruption effect (375 ms compared to 309 ms for the normal condition), $F1(1,21) = 16.58$, $p < 0.001$, $F2(1,31) = 37.59$, $p < 0.001$. This is again strong evidence that disrupting the word to the right of fixation has a disruptive effect. We also obtained an interaction between reading conditions and type of disruption for gaze duration, $F1(2,21) = 4.53$, $p < 0.05$, $F2\ (2,62) = 6.43$, $p < 0.01$, though there was no such interaction for first fixation duration, $F1(2,21) = 1.4$, $p = 0.268$, $F2 < 1$. There were no differences in gaze durations when text was presented normally, however, unsurprisingly, gaze durations were longer when word $n+1$ was disrupted than when it was not.

Examination of Table 3 reveals an interesting point regarding when the word to the right of fixation disappears or is masked at the onset of fixation. Namely, the frequency effect is somewhat attenuated for the first fixation duration data not only when the word to the right of fixation disappears or is masked, but also in the normal reading condition in comparison to when both the fixated word and the word to the right of fixation disappears or is masked (Experiments 1a and 1b and the Control experiment). That is, collapsing across normal and disrupted text conditions, the frequency effect is 23 ms in the Control experiment, 30 ms in Experiment 1a, and 24 ms in Experiment 1b. However, this effect is reduced to roughly 10 ms in Experiments 2a and 2b. Note, however, that the frequency effect for gaze duration is fairly large in Experiments 2a and 2b (we will return to this point in the General Discussion). It is also important to note that for the analyses with the Control experiment, frequency did not enter into any significant interaction in either the first fixation or gaze duration data.

Finally, again for completeness, the total fixation time data are shown in Table 3 where it is obvious that there were significant frequency effects (all ps < 0.001), as well as effects of reading condition (ps < 0.001).

9. Experiments 2a and 2b: summary

Similar to when word n disappeared and word $n+1$ disappeared or was masked after 60 ms (Experiments 1a and 1b), when only word $n+1$ either disappeared (Experiment 2a) or was masked (Experiment 2b) at the onset of fixation on word n there were longer sentence reading times and more fixations compared to when only word n disappeared (the Control experiment). In addition, fixation times were longer when the word to the right of fixation (word $n+1$) was disrupted than when it was not. These results are in line with previous studies showing that reduced preview of word $n+1$

[4] For the local analyses of word frequency for Experiments 2a and 2b, not all items produced data for each of the conditions. Consequently the items analyses for the first fixation duration measures are based on 31 items, and those for gaze duration are based on 32 items.

increases processing difficulty (Blanchard et al., 1989; McConkie & Rayner, 1975; Rayner et al., 1982). That is, preprocessing of word $n+1$ is crucial to maintaining normal patterns of reading behavior. Importantly, these results suggest that although reading can proceed normally when information from the fixated word is only available for 60 ms (Control experiment), reading cannot proceed normally when information from word $n+1$ is reduced (60 ms, Experiments 1a and 1b) or removed (Experiments 2a and 2b). These results suggest that although a 60 ms sample of linguistic information is sufficient for processing foveal text, it is not sufficient for processing these words parafoveally. Note that in Experiments 2a and 2b, word $n+1$ disappeared or was masked immediately after word n was fixated, however similar results were obtained when word $n+1$ disappeared or was masked 60 ms after word n was fixated (see Section 10 below).

As explained in the summary of Experiments 1a and 1b, the increase in average fixation durations in the disappearing conditions for Experiments 1a, 1b and the Control experiment may at least partly be explained by compensating for reduced refixation probabilities on word n when word n disappeared. However in Experiments 2a and 2b, word n did not disappear and, therefore, this explanation cannot account for the increased fixation durations here. Instead, the increase in average fixation durations was due to the reduced preview benefit from word $n+1$ (see section 12.6 below). The greater number of fixations when word $n+1$ disappeared (Experiment 2a) or was masked (Experiment 2b) compared to the normal presentation condition might be explained by the increase in refixation probabilities observed in both experiments, and also by the increased number of regressions in Experiment 2a. The increase in refixation probabilities when word $n+1$ disappeared or was masked can be explained by disruption to parafoveal processing caused by the significantly reduced preview of word $n+1$. Note that the pattern of refixation probability results in Experiments 2a and 2b is opposite to those in Experiments 1a and 1b, and those in the control experiment in which word n also disappeared. Crucially, in Experiments 1a, 1b and the Control experiment, refixating word n did not enable another sample of the linguistic information from word n (that is, word n did not re-appear); hence in the disrupted conditions in these experiments the utility of refixations was reduced and correspondingly refixation probabilities fell. In contrast, in the disrupted conditions in Experiments 2a and 2b, word n never disappeared and so refixations were effective in providing additional samples of linguistic information. Finally, and very importantly, similar to Experiments 1a and 1b, Experiments 2a and 2b clearly showed that word frequency influences first pass reading times on a word even when there is no preview (Experiments 2a and 2b) or reduced preview (60 ms in Experiments 1a and 1b) when the reader is fixating the previous word. Again, these results reflect the central role that linguistic processes play in the decision of when to move the eyes during reading.

10. Experiment 3a and 3b: global measures

Our rationale in Experiments 1a and 1b was that we wanted to examine reading performance when both word n and word $n+1$ were not available for processing 60 ms after fixation onset. Similarly, in Experiments 2a and 2b we wanted to investigate the influence of word $n+1$ disappearing, or being masked while the fixated word remained unchanged. In Experiments 2a and 2b, word $n+1$ disappeared or was masked immediately after word n was fixated. We did this because otherwise the sudden offset of the word to the right of fixation (during a fixation) might be disturbing to the reader. Because of saccadic suppression, our manipulation of word $n+1$ at the onset of a fixation should not have been extremely disruptive. However, it is also important to obtain data from a condition in which word $n+1$ alone either disappeared or was masked after 60 ms. Theoretically, the sudden offset of the word to the right of fixation could cause more disruption after 60 ms than at fixation onset because of the sudden visual change that occurred during an eye fixation (as opposed to being coincident with fixation onset). However, just the opposite result (less disruption) might also be possible because in such a situation word $n+1$ would at least be present for preprocessing for the first 60 ms of fixation.[5] In Experiments 3a and 3b then, word $n+1$ either disappeared (Experiment 3a) or was masked (Experiment 3b) after 60 ms.

10.1. Sentence reading time

The sentence reading time results were very similar to the other experiments (see Table 2). Reading was faster for the normal reading condition (3257 ms) than the disrupted conditions (3840 ms), $F1(1,21) = 39.16$, $p < 0.001$, $F2(1,39) = 53.46$, $p < 0.001$ and there were differences due to type of disruption that were apparent in the items analysis, $F1 < 1$, $F2(2,78) = 33.15$, $p < 0.001$. However, the most important result was again the significant interaction, $F1(2,21) = 10.4$, $p < 0.01$, $F2(2,78) = 34.09$, $p < 0.001$. Post hoc t tests clarified the nature of the interaction. First, there was no difference between the three normal reading conditions. Second, there were differences between the normal and disrupted conditions

[5] In recent experiments, Boot, Kramer, and Peterson (2005) have demonstrated that whereas sudden onsets have rather strong effects on eye movements, sudden offsets have very little influence on goal directed eye movements.

when word $n+1$ was disrupted. When word $n+1$ disappeared after 60 ms, reading was longer than in the normal condition, $t1(7)=4.25$, $p<0.01$, $t2(39)=9.16$, $p<0.001$. Likewise, when word $n+1$ was masked after 60 ms, reading was longer than in the normal condition, $t1(7)=7.25$, $p<0.001$, $t2(39)=9.48$, $p<0.001$. Third, reading times tended to be longer when word $n+1$ was disrupted than when only word n disappeared. This difference was significant when word $n+1$ was masked, $t1(14)=2.27, p<0.05, t2(39)=11.06, p<0.001$, and significant across items $t2(39)=7.77, p<0.001$, but not participants $t1(14)=1.31$, $p=0.212$, when word $n+1$ disappeared.

Finally, a comparison for when word $n+1$ disappeared or was masked was carried out via a 2(reading condition: normal vs disrupted) × 2(type of disruption: $n+1$ disappeared vs $n+1$ masked) ANOVA. The only reliable effect was due to reading condition, $F1(1,14)=59.18$, $p<0.001$, $F2(1,39)=174.11$, $p<0.001$, as reading was slower when there was disrupted than when there was not.

10.2. Number of fixations and fixation durations

The data pattern for number of fixations again mimicked the reading time data (see Table 2). However, the only effect that was significant in both the participants and items analyses was the interaction, $F1(2,21)=6.62$, $p<0.01$, $F2(2,78)=24.08$, $p<0.001$.

For the fixation duration data (see Table 2), the most obvious effect was that fixations were longer when word $n+1$ disappeared/was masked than when it was normal, $F1(1,21)=74.39$, $p<0.001$, $F2(1,39)=116.45$, $p<0.001$. There was also an effect of type of disruption that approached significance by participants, $F1(1,21)=3.14$, $p=0.06$, and was significant by items, $F2(1,39)=86.21$, $p<0.001$. This effect occurred due to particularly short fixation durations under the normal reading conditions. Fixation durations were also substantially reduced for the normal reading conditions in Experiment 3 when compared with those from Experiments 1 and 2. This effect was largely due to two participants whose reading times were very short relative to those of other participants who took part in these experiments. The interaction was not significant by participants, $F1(2,21)=1.42$, $p=0.265$, but was by items, $F2(2,78)=4.47$, $p<0.05$.

10.3. Regressions and refixations

For regressions (see Table 2) there were more regressions when word $n+1$ disappeared or was masked after 60 ms compared to normal reading, $F1(1,21)=11.03$, $p<.01$, $F2(1,39)=11.10$, $p<0.01$. With respect to refixation probability, like Experiments 2a and 2b, there were more refixations on word n when word $n+1$ disappeared or was masked than when the sentence was presented normally (ps < .05).

11. Experiments 3a and 3b: local measures

11.1. Frequency effects

Table 3 shows the first fixation duration, gaze duration, and total reading time measures. As per the prior experiments, we carried out 2(reading condition: normal vs disrupted) × 3(type of disruption) × 2(frequency: high vs low frequency target word) ANOVAs on the different fixation measures.[6] Once again, there were clear effects of frequency on word n even when word $n+1$ disappeared or was masked 60 ms after the onset of fixation on word n. Specifically, low frequency words received longer first fixations and gaze durations than high frequency words. First fixation duration was 259 ms for high frequency words and 284 ms for low frequency words, $F1(1,21)=23.31$, $p<0.001$, $F2(1,22)=10.73$ $p<0.01$; gaze duration was 293 ms for high frequency words and 339 ms for low frequency words, $F1(1,21)=18.62$, $p<0.01$, $F2(1,23)=10.04$, $p<0.01$.

As in Experiments 2a and 2b (but unlike Experiments 1a and 1b), there were significant effects due to reading condition with first fixations being longer when the text was disrupted (289 ms) than when it was normal (255 ms), $F1(1,21)=17.11$, $p<0.001$, $F2(1,22)=15.25$, $p<0.01$, and gaze durations likewise showing a similar disruption effect (342 ms compared to 290 ms for the normal condition), $F1(1,21)=19.86$, $p<0.001$, $F2(1,23)=15.98$, $p<0.01$. This is again strong evidence that disrupting the word to the right of fixation has a serious effect on reading.

Finally, again for completeness, the total fixation time data are shown in Table 3 where it is obvious that there were significant frequency effects (all ps < 0.001), as well as effects of reading condition (ps < 0.001).

12. Additional analyses

In addition to the analyses reported above, we also carried out analyses to determine: (1) if there were any late occurring effects related to the frequency manipulation, (2) if there were differences due to the timing of disruption to word $n+1$, (3) if there was more disruption when $n+1$ disappeared or was masked, (4) if there were differences in where the eyes landed in the target words

[6] For the local analyses of word frequency for Experiments 3a and 3b, not all items produced data for each of the conditions. Consequently, the items analyses for the first fixation duration data are based on 23 items, and those for gaze duration are based on 24 items.

as a function of the experimental manipulations, (5) if there were differences in word skipping (on first pass reading) as a function of the experimental manipulations, and (6) how parafoveal preview was affected by disruption to word $n+1$.

12.1. Delayed effects?

Two common ways to assess later occurring effects are to examine spillover effects and the probability of regressing immediately from the target word. For each of the experiments, we conducted 2(reading condition: normal vs disrupted) × 3 (type of disruption: word *n* disappeared, word $n+1$ disappeared, or word $n+1$ was masked) × 2(frequency: frequent vs infrequent) ANOVAs to examine both of these variables. Spillover refers to the fact that some processing of a target word often spills over to the next fixation. For example, spillover effects are often (though not always) found with respect to frequency effects (see Rayner, 1998). Likewise, low frequency words often induce immediate regressions back to earlier parts of the sentence. We therefore examined both spillover effects and immediate regressions from the target word. Across the experiments, there was no consistent pattern of a spillover effect. For the normal reading conditions, readers showed a 2 ms frequency spillover effect (265 ms for high frequency words vs 267 ms for low frequency words); and for the disappearing/masked text conditions there was a 1 ms effect (300 vs 301 ms).[7]

When the probability of an immediate regression was examined, we found a main effect of frequency for Experiments 1a and 1b ($ps < 0.05$, high frequency = 0.2, low frequency = 0.26), with more regressions for low than high frequency words. This effect was not reliable for Experiments 2 and 3. In addition, Experiments 1, 2 and 3 all yielded significant interactions between experiment and type of disruption ($p < 0.05$ in all cases). The basic pattern was quite similar across experiments with readers making relatively few immediate regressions under normal conditions (0.14) and under disrupted conditions in the control experiment (0.04). However, there were more regressions in the disrupted conditions for Experiments 1–3 (0.27).

Basically, the results of the spillover analyses suggest that the disrupted reading conditions did not yield any more in the way of spillover effects than did the normal reading conditions. However, when the word to the right of the fixated word was disrupted, there were clearly more immediate regressions than in either the normal reading condition or the conditions in which only word $n+1$ was disrupted.

12.2. Time of disruption

In order to determine if it made any difference if word $n+1$ disappeared or was masked coincident with the onset of fixation on word *n* or after 60 ms, we carried out analyses comparing the sentence reading times from Experiment 2a with Experiment 3a and Experiment 2b with Experiment 3b. Thus, two 2(reading condition: normal vs disrupted) × 2(time of disruption: 0 vs 60 ms) ANOVAs were performed. In both analyses, there were obvious effects of reading condition ($ps < .01$), but no consistent effect of time of disruption and no reliable interaction. Thus, the disruption caused by word $n+1$ either disappearing or being masked was not affected by whether the disruption was immediate or delayed for 60 ms. This result is quite consistent with the notion that readers would not have been able to successfully move their attention to word $n+1$ until after 60 ms, but once they did move attention to word $n+1$ there was disruption due to the word not being available.

12.3. What causes more disruption: disappearing text or masked text?

The extent to which disappearing text or masked text was more disruptive to reading can be evaluated by comparing those conditions. Thus, we conducted a 2(disappear vs mask) × 3(type of disruption: *n* and $n+1$ after 60 ms, $n+1$ after 0 ms, $n+1$ after 60 ms) ANOVA on the overall sentence reading time using only the item data. We did this because items were identical across the conditions of each experiment and therefore permit direct comparison. Not surprisingly, there was a main effect of type of disruption, $F2(1,39) = 25.2$, $p < 0.001$, since the disruption of two words yielded more disruption than word $n+1$ alone being disrupted, and a significant interaction, $F2(2,78) = 5.6$, $p < 0.01$, since the two word disruption was greater when word $n+1$ was masked than when it disappeared; in contrast, the difference between masking and disappearing text was the same when only $n+1$ was disrupted (see Table 2). However, with respect to the question of what caused more disruption, the analysis clearly revealed that masking yielded longer reading times (4583 ms) than when the same words disappeared (4120 ms), $F2(1,39) = 23.5$, $p < 0.001$.

12.4. Landing positions

Examination of the initial landing position of the eyes in the high and low frequency target words yielded three interesting results. First, there was no difference in landing position as a function of word frequency (the mean

[7] Spillover fixations can be measured in two ways: forward going fixations and all fixations. The latter group includes all fixations following fixation on the target word (including regressions). The value in the text is for forward going fixations, but the alternative spillover measure likewise yielded no effect.

landing position in high frequency words was 3.2 letters into the word and it was 3.1 letters into the word for low frequency words). Second, the eyes landed further in a word ($p < 0.01$) under the normal reading conditions (3.4 letters into the word) than when words were disrupted (2.9 letters). Third, however, there was no effect of type of disruption: the eyes landed roughly 2.9 letters into the word when it disappeared and 2.8 letters into the word when it had been masked. This latter result suggests that the additional information provided by the X mask which provided information about the exact length of the disrupted word provided no additional benefit to programming saccades. Thus, the blank space which resulted from the disappearing manipulation apparently provided as adequate a cue to word length as did the X mask.

12.5. Word skipping on first pass reading

Examination of word skipping of the high and low frequency target word revealed four interesting results. First, in the normal reading conditions, there was no difference in skipping probability as a function of frequency (with average skipping rates of approximately 10%). Second, while there was no effect of frequency on skipping in the disrupted conditions (average = 15%), readers did skip disrupted words more than normal words ($ps < .05$). Third, there was a mild tendency for more skipping when the target word disappeared (17%) than when it was masked (14%), but this effect was not close to significant ($Fs < 1$). Finally, there was a clear effect of the nature of the disruption, with skipping rates averaging 7.5% when word $n + 1$ was disrupted at the onset of fixation on word n, 14% when word $n + 1$ disappeared after 60 ms, and 26% when word n and word $n + 1$ both were disrupted after 60 ms ($ps > .01$). Interestingly, this latter condition was the most difficult overall (in terms of reading time, see Table 2), yet readers skipped the target word more frequently. Not surprisingly then, readers regressed to the target word quite frequently when both words were disrupted: when they skipped the target word, they made a fixation on the target word following a regressive saccade 78% of the time (compared to 56% of the time when they did not initially skip it).

12.6. Parafoveal preview benefit

Parafoveal preview benefit is generally computed by comparing a valid preview of a target word with either no preview or an invalid preview (Rayner, 1998). Thus, comparison of the amount of time readers looked at the high/low frequency target word in the normal reading condition with the amount of time readers looked at the same target word in the disappearing text and masked text conditions in Experiments 2 and 3 provides information about the extent to which preview effects were affected by the experimental conditions.[8] Since the experimental manipulation occurred for all words in the sentence, a given target word can be regarded as word n (when readers fixated directly on the target word), but also as word $n + 1$ when readers were fixated on the prior word. In Experiment 2 (where word $n + 1$ was not present from the onset of fixation on word n), preview benefit was 45 ms in first fixation duration and 99 ms in gaze duration (with no difference due to whether the disruption was caused by word $n + 1$ disappearing or being masked). In Experiment 3 (where word $n + 1$ disappeared or was masked 60 ms after the onset of fixation on word n), preview benefit was 53 ms in first fixation duration and 73 ms in gaze duration (again with no difference due to the nature of the disruption). The size of these preview effects is somewhat larger than the size of the effect typically found in experiments in which word $n + 1$ is either masked or replaced by other letters (see Hyönä et al., 2004).

13. General discussion

The most striking result from the present experiments is that reading was slowed down when word $n + 1$ was disrupted (either because it disappeared or was masked) either at the onset of a fixation on word n or after 60 ms. Thus, in contrast to when only word n disappeared or was masked, which caused little disruption to reading (see also Liversedge et al., 2004; Rayner et al., 2003), the disappearance or masking of word $n + 1$ caused considerable disruption to reading (specifically, reading rate). Likewise, disruption to word $n + 1$ was more problematic than disruption of word n. These results demonstrate the importance of the continued presence of the word to the right of fixation, at least beyond the first 60 ms, and possibly throughout a fixation in its entirety, in order for fluent reading to occur. Readers obtain significant preview benefit from the word to the right of fixation, and when it is disrupted in some way, reading suffers. In addition, the fact that both the disappearance of word $n + 1$ and masking of word $n + 1$ disrupted reading suggests that preprocessing of the orthographic characteristics of word $n + 1$, in addition

[8] We have previously demonstrated (see Liversedge et al., 2004) that while overall reading rates with disappearing text (when word n is disrupted) and normal text are comparable, readers use somewhat different strategies for dealing with the disappearing text. Thus, in comparison to normal reading, readers tend to make longer fixations and fewer refixations with disappearing text when word n is disrupted than is the case in normal reading. For this reason, neither the Control experiment nor Experiment 1 is a good test of preview benefit. Indeed, there was not any reliable difference between the disrupted conditions and normal reading conditions in Experiment 1 (and the Control experiment).

to processing of basic visual information such as word length, must occur.

As noted above, reading was disrupted more by the disappearance of word $n+1$ (Experiments 2a, 2b, 3a, 3b) than that of word n (Control experiment). This result suggests that in order for normal reading to occur, readers require the information from parafoveal words (word $n+1$) to be available throughout fixation (or at least beyond the first 60 ms of a fixation), whereas a brief exposure (of 50–60 ms) is only required for foveal words (word n). Also, the disruption caused when word n disappears and word $n+1$ disappears (Experiment 1a) or is masked (Experiment 1b) is numerically greater than when only word $n+1$ disappears (Experiments 2a and 3a) or is masked (Experiments 2b and 3b). These results suggest that removing or masking information from both word n and word $n+1$ is more disruptive to reading than only removing or masking information from word $n+1$. Critically, these findings suggest that when reading disappearing text (Liversedge et al., 2004; Rayner et al., 2003), readers require not only the 60 ms of foveal information (word n), but they are also highly dependent on the availability of parafoveal information (word $n+1$) in order to maintain normal reading.

While it is clearly the case that reading was disrupted when word $n+1$ either disappeared or was masked, it is also very interesting that frequency effects remained robust across the various experiments. Even when word n disappeared or was masked, or when word $n+1$ disappeared or was masked, there was a clear effect of the frequency of word n on readers' eye fixations. It is quite interesting that in Experiments 2 and 3, the size of the frequency effect in the gaze duration data for the disrupted conditions was roughly double that of the normal reading condition. This effect is largely driven by the fact that refixations occurred because word n remained throughout the fixation in comparison with Experiment 1 and the Control experiment (where the fixated word disappeared after 60 ms). As we (Liversedge et al., 2004; Rayner et al., 2003) noted previously, the fact that the frequency effect maintains across these conditions is very consistent with models in which cognitive/linguistic processing determines when the eyes move.

Why is reading disrupted when word $n+1$ disappears or is masked? We suspect, again consistent with a model like the E-Z Reader model (Reichle et al., 1998, Reichle, Rayner, & Pollatsek, 2003), that the reason is because much of the time when the eyes are fixated on word n, processing is underway for word $n+1$ (with processing of that word and programming the next saccade taking place in parallel). In the E-Z Reader model, at a certain point when the eyes are still on word n, attention shifts to word $n+1$. If word $n+1$ disappears or is masked, then the normal processing associated with that word is disrupted. Recent simulations using the E-Z Reader model (Pollatsek, Reichle, & Rayner, 2005; Rayner, Reichle, & Pollatsek, 2005; Reichle, Pollatsek, & Rayner, 2005) have successfully captured the general pattern of data presented in this article in the case when word $n+1$ disappears.

For all of the experiments reported here, sentence reading times were longer when word $n+1$ was masked compared to when it disappeared. It appears that providing word length information (via the mask) in the absence of orthographic information provides no additional advantage. In fact, the masking pattern of X's produced, if anything, more disruption to reading than simply making the word disappear. There are at least two possible explanations for this pattern of results. The first is that the effect is due to a form of forward masking in which processing of the masking pattern interferes with recognition of the word when it is subsequently fixated. That is, the X mask in the parafovea may interfere with subsequent letter extraction for word $n+1$ when it is directly fixated. An alternative explanation is that the masking pattern may have been sufficiently salient as to attract attention from word n to word $n+1$ during fixation of word n. Such a shift of attention would have afforded no processing advantage in terms of the availability of linguistic information from the parafovea. Furthermore, it may have disrupted lexical processing since, under such circumstances, processing of the fixated text would be reduced. In other words, disruption might have occurred both because attention is shifted (a) away from a word that is available to be processed and (b) towards a parafoveal word that is not available to be processed due to the presence of an X mask that interferes with ongoing lexical processing.

14. Summary

The experiments reported here clearly demonstrate the importance of the word to the right of fixation in reading. The most disruption to reading occurred when the fixated word and word $n+1$ both disappeared (or were masked), but there was also considerable disruption when only word $n+1$ disappeared (or was masked). This latter finding stands in sharp contrast to when only the fixated word (word n) disappeared (or was masked); this caused virtually no disruption to reading (see also Liversedge et al., 2004; Rayner et al., 2003). Finally, the results again demonstrate the robustness of the frequency effect in reading. Across the various experiments reported here, the frequency of the currently fixated word influenced how long readers looked at that word quite independent of word n and/or word $n+1$ disappearing (or being masked).

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