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Rayner, K., Liversedge, S.P., White, S.J., & Vergilino-Perez, D. (2003). Reading disappearing text: Cognitive control of eye movements. *Psychological Science, 14*, 385-388.

NOT THE FINAL PUBLISHED VERSION

Reading Disappearing Text:
Cognitive Control of Eye Movements

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Running Head: Reading Disappearing Text
Word Count = 2499

Abstract

Readers read sentences containing high or low frequency target words under normal reading conditions or disappearing text conditions (in which the word that was fixated disappeared after 60 ms). Even though the fixated word had disappeared after 60 ms, there was still a robust frequency effect wherein readers fixated longer on low frequency words than on high frequency words. As such, the results are consistent with cognitive control models of eye movement control and inconsistent with visual/oculomotor control models. While the uptake of visual information is clearly important for reading, it is the cognitive processes associated with understanding the fixated words that drive the eyes through the text.

It is well-known that readers make a series of eye movements (called saccades) separated by fixations (Rayner, 1998). It is during the eye fixations (which typically last 200-300 ms) that new information is acquired by the processing system and the mental representation of what the text means is constructed. Eye movements are critical because they mediate the complex sequence of cognitive processes that are involved in first extracting the required visual information from the text and secondly the interpretation of that information. The question we address in this article is: What determines when the eyes move during reading? Three general types of models have been proposed to account for eye movement control in reading: minimal control, visual/oculomotor control, and cognitive control.

According to the minimal control view (Bouma & deVoogd, 1974; Kolers, 1976; Suppes, 1994), there is no relationship between eye movements and linguistic processing of the text: eye movements serve the function of bringing new information into the processing system, but there is no relationship between how long a reader fixates on a particular word and any linguistic property of that word. However, this view has been largely abandoned due to numerous findings demonstrating that how long a reader looks at a word is influenced by the ease or difficulty associated with processing that word (see Rayner, 1998, for a review). Perhaps the major mitigating finding against the minimal control view is the word frequency effect: readers look longer at low frequency words than at high frequency words (Inhoff & Rayner, 1986; Rayner & Duffy, 1986). This effect is quite robust and has been demonstrated many times (Rayner, 1998), and is one we utilize in the present experiment.

The visual/oculomotor control view (O'Regan, 1992; Yang & McConkie, 2001) holds

that the primary determinant of when to move the eyes is the visual/oculomotor processes associated with reading. According to this view, when the eyes move is only indirectly related to the mental activities associated with ongoing language processing. O'Regan (1992) suggested that linguistic factors influence the duration of a single long fixation (300 ms or longer), and only the second of two fixations when words are refixated (i.e., receive additional fixations prior to the reader moving to another word). Yang and McConkie (2001) likewise argued that cognitive processing activities only influence long fixations and variations in fixation times have little relation to a reader's current cognitive activity. Yang and McConkie do not deny that there are linguistic influences on fixation times (such as the word frequency effect). But, within their Competition-Interaction model most of the variation in fixation time is due to physiological/visual processes that have little relation to the current cognitive activity (pg 3584). A basic feature of their model is that when cognitive factors influence eye fixations it is by canceling (and reprogramming) a saccade (as opposed to cognitive activities initiating a new saccade as in the cognitive control models).

According to the cognitive control view (Morrison, 1984; Reichle, Pollatsek, Fisher, & Rayner, 1998; Reichle, Pollatsek, & Rayner, 1999; Reichle, Rayner, & Pollatsek, 2002; Henderson & Ferreira, 1990), linguistic processing of the text largely determines when the eyes move. For example, in the E-Z Reader model (Reichle et al., 1998), a familiarity check that precedes lexical access serves as the signal for the initiation of an eye movement and completion of lexical access is the signal for a shift of covert attention from the fixated word to the next word in the text. This type of model can easily account for the fact that low frequency words are fixated longer than high frequency words.

In the present study, we used a novel paradigm in which text literally disappeared from before a reader's eyes (see Figure 1) to further determine what controls when the eyes move in reading. Each time the eyes fixated on a word, it disappeared after 60 ms. When readers moved their eyes to a new word, it too disappeared after 60 ms. An immediate refixation on the disappearing word was not functional in that it did not result in that word reappearing. With this paradigm, we compared fixation times on high and low frequency words when readers read normal and disappearing text. Cognitive control models predict that the frequency effect should emerge independent of whether readers read normal or disappearing text. That is, since it is the mental activities associated with processing a given word that drive the eyes through the text, readers should remain fixated on a low frequency word longer than on a high frequency word, even though the word has disappeared. Since there are variations of visual/oculomotor models, they might differ somewhat in the prediction that they make about what should happen when reading disappearing text. However, it seems that in general they should predict no difference between how long readers look at high and low frequency words under disappearing text conditions. That is, since the visual information needed for reading is gone after 60 ms, the eyes should move after approximately the same amount of time regardless of whether readers fixate low or high frequency target words.

Insert Figure 1 about here

Method

Participants. Eight undergraduate students at the University of Durham participated in the experiment. They were all skilled readers with normal uncorrected vision, native

speakers of English, and naïve concerning the purpose of the experiment.

Materials and Design. There were 40 experimental sentences. For each sentence, two versions were created. In one version, a high frequency target word was embedded in the sentence; in the second version, a low frequency word occupied the same location as the high frequency word. Either word fit naturally in the sentence. Some example sentences with high and low frequency target words are shown in Table 1.

Insert Table 1 about here

Word frequencies were calculated using the CELEX English word form corpus (Baayen, Piepenbrock, & Gulikers, 1995). The frequent words had a mean frequency of 105 per million (range: 18-970) and the low frequency words had a mean frequency of 1 (range: 0-7). Each sentence was one line of text (with no more than 80 character spaces per line). The 40 experimental sentences were presented in two blocks (one in normal text format and one in disappearing text format). The order of blocks was counterbalanced across participants so that each of them received high or low frequency target words under the normal or disappearing condition equally often. Five practice sentences were presented at the beginning of each block and 8 comprehension questions were presented in each block; these questions appeared on the video monitor and participants responded by pushing one button for a 'yes' answer and another button for a 'no' answer.

Apparatus. The sentences were presented on a Phillips 21B582BH 21 inch monitor (with a P22 phosphor with a decay to zero in less than 1.7 milliseconds) interfaced with a Phillips Pentium III computer, which in turn was interfaced with a Fourward Technologies Dual-Purkinje Generation 5.5 eye-tracker (with spatial resolution of less than 10 min of arc).

The sentences were displayed as white letters (in lower case except where capital letters were appropriate) on a black background. Five characters subtended one degree of visual angle. Viewing was binocular, but only the movements of the right eye were monitored. Eye position was sampled every millisecond and the fixated word disappeared 60 ms after the computer determined that the eye had fixated on the word¹.

Procedure. Participants were instructed to read the sentences so that they understood them, regardless of how they were presented on the monitor (i.e., normal text or disappearing text). A bite bar and head restraint were used to minimize head movements. The initial calibration procedure lasted approximately 5 minutes and calibration accuracy was checked prior to every trial in the experiment. After reading each sentence, the participants pressed a button to continue; the button press resulted in either a comprehension question or the calibration pattern followed by the next sentence in the sequence.

Results

Although the disappearing text situation might appear to be somewhat bizarre, readers could read quite easily. Indeed, their reading rate (265 wpm for disappearing text and 270 wpm for normal text) and comprehension level were the same for disappearing (94% correct) and normal text (96% correct).

Consistent with standard practices in eye movement research (Rayner, 1998; Liversedge & Findlay, 2000), we examined three measures of initial processing time for the target words: single fixation duration (where readers made only one fixation on the target word), first fixation duration (the duration of the first fixation on a word independent of the number of fixations that were made on the word), and gaze duration (the sum of all fixations on a word before moving the eyes off that word). Since gaze duration is typically considered

the best measure of processing time for a word, we will present those data first. For each of the three measures, 2 (text: normal vs. disappearing) X 2 (frequency: high vs. low) analyses of variance were carried out based on participant (F1) and item variability (F2).

Insert Table 2 about here

Table 2 shows the means for the three measures of processing time. For gaze duration, there was a very robust effect of frequency as readers fixated longer on low frequency words (331 ms) than on high frequency words (290 ms), $F(1,7) = 18.02, p < .005$; $F(1,39) = 11.09, p < .005$. However, there was no effect of text condition ($F_s < 1$) and no interaction ($F_s < 1$).

The first fixation and single fixation duration data were consistent with the gaze duration data. For single fixation duration, there was again a significant frequency effect, $F(1,7) = 10.75, p < .05$; $F(1,39) = 22.02, p < .001$, as the low frequency words (303 ms) were fixated longer than high frequency words (267 ms), but neither the main effect of text ($p_s > .15$) nor the interaction ($p_s > .25$) was significant. For first fixation duration, there was again a robust frequency effect with longer fixations for low frequency words (295 ms) than high frequency words (266 ms), $F(1,7) = 13.06, p < .01$; $F(1,39) = 11.02, p < .005$. Neither the main effect of text, $F(1,7) = 4.38, p > .07$; $F(1,39) = 3.82, p > .05$, nor the interaction ($F_s < 1$) was significant. The tendency for slightly longer first fixations for disappearing text was offset by the fact that readers were much less likely (6.5%) to refixate on the target word with disappearing text than with normal text (14%), $F(1,7) = 9.0, p < .05$; $F(1,39) = 5.32, p < .05$. Of course, the differences in refixation tendency combined with the fixation times to yield virtually equivalent means for normal and disappearing text in the gaze duration measure.

Insert Figure 2 about here

Consistent with prior research (Rayner, 1995), the distribution for the normal reading

condition showed a clear rightward shift in the frequency distribution for low frequency words relative to high frequency words². The disappearing text condition likewise showed a shift of the distribution (see Figure 2). Thus, it is the case that the difference in mean gaze durations for high and low frequency words was not due to a number of very long gaze durations as the visual/oculomotor control models would suggest.

Discussion

Our results demonstrate that it is the mental processes associated with understanding the fixated word that determine when the eyes move in reading. Even though the fixated word disappeared after 60 ms, readers continued fixating longer on the location of where the word had been for low frequency words than for high frequency words. As such, the results are consistent with cognitive control models, such as the E-Z Reader model (Reichle et al., 1998), which posit that lexical processing determines when the eyes move. Furthermore, the results are inconsistent with visual/oculomotor models, such as the Competition-Interaction model of Yang and McConkie (2001). According to Yang and McConkie (2001), cognitive processing activities mainly serve to delay the onset of the next saccade by cancelling and reprogramming a new saccade (and they used abrupt onsets and offsets to demonstrate such effects). Thus, the disappearance of the fixated word in our study should delay the onset of the next saccade. Indeed, in the case of first fixation duration (and single fixation duration) there was a 20 ms delay in the next saccade under disappearing text conditions. However, this was offset by the fact that readers were much less likely to refixate on a word in the disappearing text condition than in the normal text condition. This resulted in equivalent gaze durations on the target words in the disappearing and normal text conditions. Furthermore, the fact that the size of the frequency effect was equivalent across the disappearing and normal text conditions is difficult for the visual/oculomotor control models to explain, whereas the result is easily explainable within cognitive control models.

Not only are our results consistent with cognitive control models, they are also consistent with prior research which demonstrated that when text was available for 50-60 ms before a masking pattern appeared, reading was quite normal (Rayner, Inhoff, Morrison, Slowiaczek, & Bertera, 1981; Slowiaczek & Rayner, 1987; Ishida & Ikeda, 1989). This does not mean that the mental processes associated with reading are completed in 50-60 ms, but rather that this is the time required for retinal stimulation to produce excitation in the visual cortex, thus providing the visual information necessary for cognitive processing to occur. This short neural transmission time ensures that visual information is delivered to the cognitive system very rapidly thereby enabling readers to make short eye fixations, typically lasting approximately 200-300 ms.

In conclusion, the experiment presented here provides clear support for cognitive control models of eye movements in reading. While the uptake of visual information is important and necessary for reading to occur, it is the mental operations on that information that drive the eyes through the text.

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Acknowledgments

This research was conducted when the first and fourth authors were visitors at the University of Durham. It was supported by National Institute of Health Grant HD26765 and by a grant from The Leverhulme Trust (United Kingdom) which supported the first author as a Leverhulme Visiting Professor at the University of Durham. The fourth author was supported by a Post-Doctoral Fellowship from the Foundation Fyssen (France). The authors thank Bob Metcalfe for programming assistance and John Findlay, John Henderson, Albrecht Inhoff, and Bob Kentrige for their helpful comments.

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Footnotes

1. We performed a shutter test (Irwin, Yantis, & Jonides, 1983) to ensure that phosphor persistence did not enable readers to see a fading image of the fixated word. Four participants, who did not participate in the main experiment, were asked to perform a lexical decision task for words and non-words presented centrally on the video monitor used in the main experiment. A fixation cross was initially presented followed by a letter string which was presented for 60 ms. A shutter device was programmed to close simultaneously with the presentation of the letter string and to open coincident with the offset of this stimulus. If there were a fading image due to phosphor persistence, the participants should have been able to accurately respond in the task. However, all of them found the task virtually impossible (they were all convinced that nothing had been presented prior to the shutter opening, except for the fixation cross) and performance for all four participants was completely at chance. Thus, it is clear that phosphor persistence was not contributing to the results.
2. The frequency distributions for single fixation and first fixation duration likewise showed a rightward shift of the distribution for low frequency words (for both the normal and disappearing text conditions).

Table 1. Example sentences with the high and low frequency target word

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

Note: all target words were 6 letters long.

Table 2. Single Fixation Duration (SFD), First fixation duration (FFD), and Gaze Duration (GD) means (in ms) as a function of text condition and frequency.

	SFD	FFD	GD
Normal Text			
High Frequency	257	256	289
Low Frequency	298	288	328
Disappearing Text			
High Frequency	277	276	291
Low Frequency	307	301	333

Figure Captions

Figure 1. Example of disappearing text. When the reader fixated on the word *church* it was visible for 60 ms. Then it disappeared until the reader made a fixation on a new word. Thus, an immediate refixation on *church* did not result in it reappearing. However, if the reader fixated on *underwent* (which disappeared after 60 ms) and then went back to *church*, it would again be visible for 60 ms before disappearing. Each word in the sentence that the reader fixated (beginning with the first word in the sentence) likewise disappeared after 60 ms of each fixation. The asterisk indicates fixation location.

Figure 2. Frequency distribution of gaze durations for low and high frequency words in the disappearing text condition (35 ms bins).

The really marvellous church	*	underwent shoddy	New Fixation
The really marvellous		underwent shoddy	After 60 ms
	*		
The really marvellous church		underwent shoddy	New Fixation
		*	
The really marvellous church		shoddy	After 60 ms
		*	

