*Psychonomic Bulletin & Review*
*2007, 14 (4), 762-769*

# Word frequency and predictability effects in reading French: An evaluation of the E-Z Reader model

Sébastien Miellet
*University of Glasgow, Glasgow, Scotland*

Laurent Sparrow
*Université de Lille III, Villeneuve d'Ascq, France*

and

Sara C. Sereno
*University of Glasgow, Glasgow, Scotland*

French readers' eye movements were monitored as they read a passage of text. Initial global analyses of word frequency, accounting for the majority of fixations in the text, revealed a good fit between the observed data and the simulated data from the E-Z Reader 7 model of eye movement control. However, the model did not perform as well on simulations of contextual predictability effects. A subset of 20 controlled words from the passage were used to examine the combined effects of frequency and predictability. Results from the observed data showed main effects of frequency and predictability but no interaction. With certain modifications, the E-Z Reader 7 model was able to adequately simulate the pattern of data. Although the E-Z Reader model successfully accounted for the present data, we believe that further modifications will be necessary in order to better account for data in the literature.

The study of eye movements has long been considered a profitable way to investigate cognitive processes in reading (Huey, 1908; Javal, 1906; Rayner, 1998). Oculomotor measures both are sensitive to a large number of cognitive processes and can be obtained under relatively natural conditions. Formal modeling of eye movement control during reading is one approach that can permit a better understanding of the underlying oculomotor and linguistic processes. Because a model's predictions can be compared with observed reading behavior, testable predictions can be generated, and the model can be incrementally modified. The E-Z Reader model of eye movement control (Pollatsek, Reichle, & Rayner, 2006; Reichle, Pollatsek, Fisher, & Rayner, 1998; Reichle, Rayner, & Pollatsek, 2003) is the most influential model at present. A central tenet of E-Z Reader is that visual attention is allocated serially across words in reading. This contrasts with other models of eye movement control, such as SWIFT, in which attention is distributed as a gradient and lexical access can occur in parallel (Engbert, Nuthmann, Richter, & Kliegl, 2005). E-Z Reader was inspired by Morrison's (1984) model, which uncoupled eye movements from attentional shifts (see also James, 1891). In E-Z Reader, lexical access occurs over two stages. Completion of the first stage of lexical access (L1, or the *familiarity check*) signals saccadic programming to begin, and completion of the second (L2, or the *completion of lexical access*) signals the attentional *spotlight* to shift to the next word. The main factors affecting both stages of access are word frequency and contextual predictability.

When we undertook this study, the E-Z Reader predictions had been compared only with the results of Schilling, Rayner, and Chumbley (1998), a study in which word frequency was manipulated. Since then, Rayner, Ashby, Pollatsek, and Reichle (2004) used E-Z Reader to model their eye movement data on word frequency and contextual predictability. Our aim was to test whether the model could be generalized to the reading of French in investigations of the relationship between frequency and predictability.

The individual effects of frequency and predictability are well established in the eye movement literature. High-frequency (HF) words are fixated for shorter durations than are low-frequency (LF) words (e.g., Rayner & Duffy, 1986; Rayner, Sereno, & Raney, 1986; Sereno & Rayner, 2000). Similarly, high-predictable (HP) words (i.e., more constrained by prior context) are fixated for shorter durations and are more likely to be skipped than are low-predictable (LP) words (e.g., Balota, Pollatsek, & Rayner, 1985; Ehrlich & Rayner, 1981; Rayner & Well,

S. Miellet, miellet@psy.gla.ac.uk

1996). Nevertheless, few eye movement studies have been done to examine these influential variables simultaneously. Early reaction time studies examined both factors and typically showed main effects of frequency and predictability and, critically, a significant interaction, with predictability having a more beneficial effect for LF words (e.g., Stanovich & West, 1983). Arguably, however, the paradigms used (lexical decision and naming) involve the recruitment and application of strategies not found in normal reading. A recent electrophysiological study also showed an interactive pattern for frequency and predictability in the N1 component (first negative-going wave) beginning at 132 msec poststimulus (Sereno, Brewer, & O'Donnell, 2003). However, the presentation rate was relatively slow, as compared with normal reading (~500 msec per word), and the effect of predictability for LF words was marginal. In an early reading study, Inhoff (1984) also found an interaction in gaze duration. However, these results represented combined data from normal reading and a condition in which there was a three-character moving foveal mask. In addition, word length was not formally controlled.

More recently, three eye movement studies have been carried out that orthogonally varied the frequency and predictability of target words embedded in sentences (Altarriba, Kroll, Sholl, & Rayner, 1996; Lavigne, Vitu, & d'Ydewalle, 2000; Rayner, Binder, Ashby, & Pollatsek, 2001). These studies consistently showed, with respect to fixation time, main effects of frequency and predictability but failed to show a significant interaction. It is important to note that the relationship between frequency and predictability was not the principal focus of these studies. Although it was the focus of Rayner et al.'s (2004) study, they also found no evidence of a frequency × predictability interaction. They did find a reliable interaction, however, for the probability of skipping the target, different from the pattern in reaction time studies, with increased skipping for HF–HP words.

In the present study, we sought to extend these findings. First, word frequency and predictability effects were tested in French, using target words embedded in a short story. Prior eye movement studies have typically used targets in a series of single-line, unrelated sentences. Second, the data were compared with different simulations of E-Z Reader.

## METHOD

### Participants

Fifteen naive volunteer graduate students from the University of Lille 3, all native French speakers having normal, uncorrected vision, participated in the experiment (average age = 22.3 years).

### Apparatus

Although viewing was binocular, eye movements were recorded, via an AMtech ET4 pupil-tracking system, from the right eye. The eyetracker has a spatial resolution of 2 min of arc, and its signal was sampled every 5 msec by a 586 computer. The text was displayed on a 17-in. View Sonic monitor in conventional upper- and lowercase characters. At a viewing distance of 75 cm, 3.4 characters subtended 1º of visual angle.

The text was presented in a nonproportional font, using white characters on a black background. Monitor luminance was adjusted to a comfortable level and was held constant throughout the experiment.

### Materials and Design

The participants read a meaningful short story of 134 words. For each word, its length, frequency, and contextual predictability values were obtained. Predictability was determined by a cumulative Cloze task involving a different set of 20 participants.[1]

A set of 20 target words was selected on the basis of several properties (see the Appendix). First, all the targets appeared near the middle of a line of text. Ten were HF and 10 were LF words. Word frequencies were determined from LEXIQUE, a corpus of 14.8 million words (New, Pallier, Ferrand, & Matos, 2001). The mean frequency per million was 457 for HF words (all HF > 200) and 19 for LF words (all LF < 30). For each frequency group, half were HP and half were LP words. The Cloze probabilities were .71 for HP words (all HP > .50) and .04 for LF words (all LP < .20). Target words ranged from 5 to 10 characters ($M = 6.35$).

### Procedure

The participants sat in a dimly illuminated room in front of the eyetracker, resting their head within a chinrest. A flexible band around their heads was gently tightened to minimize head movements. The participants were informed that they would be presented with two short stories. They were instructed to read at a normal pace, paying attention to meaning. The first story allowed them to become familiar with the procedure. The second was the experimental passage, presented over four successive screens of text, with up to seven double-spaced lines of text per screen and up to 49 characters per line.

Prior to presentation of each screen of text, a fixation cross appeared in the upper left, marking the first character position of text. When the participants' eye position was aligned with this cross, it disappeared, and the first screen of text was presented. When the participants had finished reading the screen of text, they fixated another cross at the bottom right of the screen. When the eye position was aligned with this cross, the screen of text disappeared, and the upper cross reappeared. The calibration was checked and, when necessary, recalibrated.

After reading the experimental passage, the participants paraphrased the story to ensure that they had maintained attention. None had any difficulty in summarizing the story.

## RESULTS

Data were excluded from the analyses when fixation times were beyond a ±1.64 standard deviation value calculated for each participant, resulting in a 10% data loss. The data were analyzed in terms of several standard eye movement measures. The target region included the space before the word and the word itself. First-fixation duration (FFD) represents the duration of an initial fixation on a word when approached from the left (i.e., the word has not already been skipped). Gaze duration (GD) represents the sum of all consecutive first-pass fixations made on a word prior to an eye movement to another word; if a word is fixated only once, FFD and GD are identical. Single-fixation duration (SFD) represents those cases in which a word is fixated only once. Finally, the probability of skipping (PrSkip) a word on a first-pass fixation was also calculated.

Several analyses were conducted. First, we examined global eye movement behavior across the entire experimental passage and compared the observed data with the predicted values generated by E-Z Reader 7 (Reichle et al., 2003). Second, we analyzed the selected 20 words for frequency and predictability effects. We also compared these results with different versions of E-Z Reader 7: the original multiplicative version; the extended, additive version (Rayner et al., 2004); and a modified extended, additive version.[2]

**Global Behavior**

We compared a simulation using the original parameters of E-Z Reader 7 (based on those used to simulate the Schilling et al., 1998, data) with empirical data representing the majority of the 134-word text. For each word, we specified its position, length, frequency, and predictability. In accordance with E-Z Reader 7, the first and last words of each line of text were excluded from the simulation.[3] The remaining 90 words were categorized, as in Schilling et al. (1998), into five frequency bands (1–5) from low to high frequency (see Table 1).

As is shown in Figure 1, we obtained satisfactory matches between most observed and predicted values for

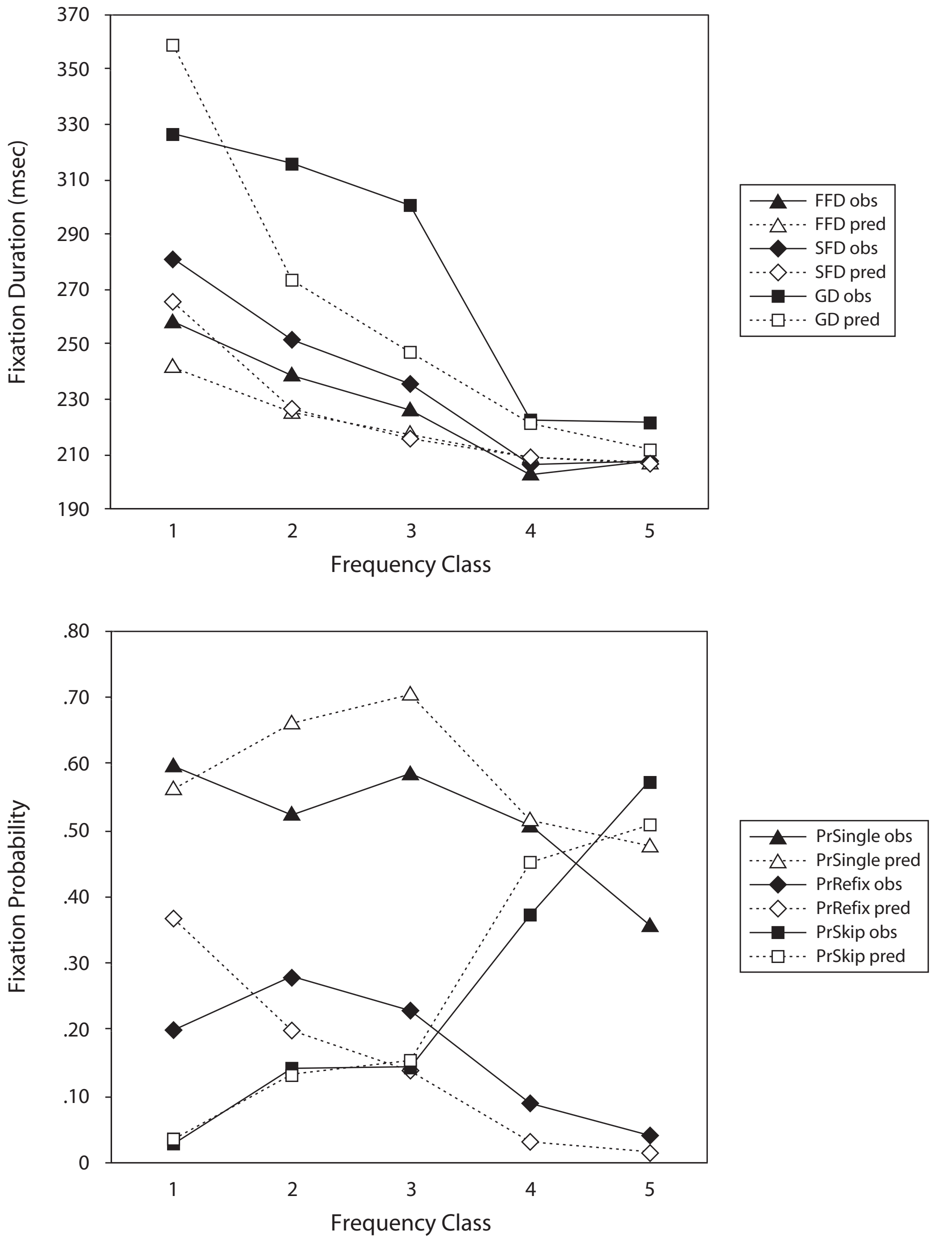


**Figure 1. Top: Mean observed (obs) and predicted (pred) fixation duration values for first-fixation duration (FFD), single-fixation duration (SFD), and gaze duration (GD) for five frequency classes of words (Bands 1–5, from low to high frequency) (RMSD = 0.452). Bottom: Mean observed (obs) and predicted (pred) probability values for single fixation (PrSingle), refixation (PrRefix), and skipping (PrSkip) for five frequency classes of words (Bands 1–5, from low to high frequency) (RMSD = 0.452).**

**Table 1**
**Specifications of Word Targets Across Different Analyses**

| | *N* | Length | Frequency | Predictability |
|---|---|---|---|---|
| Global Test of Word Frequency | | | | |
| Frequency Group | | | | |
| 1 (0–10) | 2 | 6.5 | 6 | .50 |
| 2 (10–100) | 15 | 7.7 | 31 | .22 |
| 3 (100–1,000) | 23 | 6.5 | 359 | .20 |
| 4 (1,000–10,000) | 19 | 4.1 | 4,617 | .57 |
| 5 (10,000–100,000) | 31 | 2.9 | 23,052 | .49 |
| Global Test of Predictability | | | | |
| Predictability | | | | |
| LP | 39 | 6.1 | 40 | .02 |
| HP | 35 | 4.1 | 123 | .81 |
| Global Test of Frequency × Predictability | | | | |
| Condition | | | | |
| LF–LP | 25 | 7.1 | 2 | .02 |
| LF–HP | 9 | 6.3 | 2 | .76 |
| HF–LP | 14 | 4.2 | 96 | .03 |
| HF–HP | 26 | 3.2 | 165 | .82 |
| Frequency × Predictability for 20 Controlled Targets | | | | |
| Condition | | | | |
| LF–LP | 5 | 6.0 | 17 | .05 |
| LF–HP | 5 | 7.0 | 22 | .73 |
| HF–LP | 5 | 6.8 | 527 | .03 |
| HF–HP | 5 | 5.6 | 387 | .68 |

Note—*N* represents the number of words from the 134-word text used. The average word length is measured in characters. The average word frequency is measured in occurrences per million. The average predictability of a word is measured as the probability of guessing that word in a cloze task. The top three groupings represent a majority sample of words from the text (global tests), whereas the bottom grouping represents the selection of 20 words. LF, low frequency; HF, high frequency; LP, low predictability; HP, high predictability.

fixation time (top panel) and fixation probability measures (bottom panel). The biggest disparity was between observed and predicted values in GD for medium- to high-frequency words (Bands 2–3), where observed values were longer. In the reference experiment used to test the model (Schilling et al., 1998), the sentences tended to be short, stereotyped expressions that were quite simple to comprehend. Our story was more complex, engaging a deeper level of processing, and this might explain why GDs were longer for these words. Despite these disparities, the overall fit, considering the use of different participants reading a passage in a different language, was quite good. In general, goodness of fit is the error in prediction on key variables—namely, fixation duration and fixation probabilities. This is usually expressed as a mean-squared error for each variable, which can be summed and/or transformed into a single deviation measure (for further discussion, see Engbert et al., 2005).

We also examined global effects of predictability. From the 90-word sample, a subset of 74 words were chosen with cloze probabilities either greater than .60 for HP words or less than .10 for LP words (see Table 1). In general, predictability effects tend not to be as pronounced in fixation time as frequency effects (see Sereno, O'Donnell, & Sereno, 2003) and are often expressed in terms of increased word skipping. In our study, readers skipped 31% of the HP words, as compared with 22% of the LP words. E-Z Reader 7 produced similar values, with skipping rates of 37% for the HP and 25% for the LP words. The difference between HP and LP skipping rates (9% in our study, 12% for E-Z Reader) was consistent with that in prior research (Rayner et al., 2001; Rayner & Well, 1996).

The pattern of observed versus predicted results for fixation times was less consistent (see Table 2). The observed data showed numerical differences for predictability in FFD, SFD, and GD measures. E-Z Reader 7, however, showed substantial predictability differences only for GD. Although the GD difference is smaller than ours, it is comparable to those in other eye movement studies (Rayner et al., 2001; Rayner & Well, 1996).

We then categorized the 74 HP and LP words by frequency (see Table 1). Fixation time and probability measures for these data, as well as the simulated data from E-Z Reader 7, are shown in Table 3. A qualitative comparison of the data revealed an overall good fit, with two exceptions. First, the size of the predictability effect in the simulation for LF words in FFD and SFD was larger than what was observed. More problematic, however, was that E-Z Reader showed a reverse predictability effect for HF words; that is, fixation times were longer for HP than for LP words. The sample of words used in this analysis confounded word length and frequency; that is, HF words also tended to be shorter (see Table 1). We thus focused on a set of 20 target items in which length, frequency, and predictability were more tightly controlled (see Table 1).

## Frequency × Predictability

Fixation time[4] and skipping probability data for the sample with 20 target words are shown in Table 4. The mean launch distance was 5.86 characters and did not differ across conditions (all $F$s $< 1$). A 2 (frequency: LF vs. HF) × 2 (predictability: LP vs. HP) ANOVA was carried out on the fixation duration and skipping probability means, both by participants ($F_1$) and by items ($F_2$).

A main effect of the frequency was observed for FFD and GD, with longer fixation times on LF than on HF words [FFD, $F_1(1,14) = 16.74$, $p < .01$, and $F_2(1,16) = 25.58$, $p < .001$; GD, $F_1(1,14) = 7.93$, $p < .05$, and $F_2(1,16) = 12.20$, $p < .01$]. A main effect of predictability was observed only for FFD, with longer fixations on LP than on HP words [$F_1(1,14) = 5.36$, $p < .05$; $F_2(1,16) =$

**Table 2**
**Mean Observed and Predicted Fixation Durations (in Milliseconds) on Low- and High-Predictable Words**

| Measure | Data Type | LP | HP | LP − HP |
|---|---|---|---|---|
| FFD | Observed | 226 | 207 | 19 |
| | Predicted | 213 | 209 | 4 |
| SFD | Observed | 232 | 212 | 20 |
| | Predicted | 212 | 209 | 3 |
| GD | Observed | 280 | 235 | 45 |
| | Predicted | 240 | 223 | 17 |

Note—Fixation time measures include first-fixation duration (FFD), single-fixation duration (SFD), and gaze duration (GD). Observed data correspond to the set of 74 words, and predicted data are derived from a simulation of E-Z Reader 7. The targets were either low-predictable (LP) or high-predictable (HP) words.

**Table 3**
**Mean Observed and Predicted Fixation Durations (in Milliseconds) and Fixation Probabilities on Low- and High-Frequency, and Low- and High-Predictable Words**

| | | LF | | | HF | | |
|---|---|---|---|---|---|---|---|
| Measure | Data Type | LP | HP | LP − HP | LP | HP | LP − HP |
| FFD | Observed | 232 | 217 | 15 | 220 | 198 | 22 |
| | Predicted | 229 | 200 | 29 | 198 | 219 | −21 |
| SFD | Observed | 240 | 225 | 15 | 223 | 199 | 24 |
| | Predicted | 229 | 199 | 30 | 196 | 219 | −23 |
| GD | Observed | 307 | 252 | 55 | 253 | 217 | 36 |
| | Predicted | 270 | 222 | 48 | 210 | 224 | −14 |
| PrSingle | Observed | .61 | .68 | | .50 | .46 | |
| | Predicted | .71 | .69 | | .54 | .45 | |
| PrRefix | Observed | .28 | .18 | | .12 | .07 | |
| | Predicted | .18 | .10 | | .06 | .01 | |
| PrSkip | Observed | .11 | .14 | | .38 | .48 | |
| | Predicted | .11 | .20 | | .40 | .53 | |

Note—Fixation time measures include first-fixation duration (FFD), single-fixation duration (SFD), and gaze duration (GD). Fixation probability measures include the probability of a single fixation (PrSingle), the probability of a refixation (PrRefix), and the probability of skipping (PrSkip). Observed data correspond to the set of 74 words, and predicted data are derived from a simulation of E-Z Reader 7. Targets were either low- or high-frequency (LF or HF) words of either low or high predictability (LP or HP).

8.12, $p < .05$]. For GD, although the pattern of means was similar to that for FFD, the predictability effect was not significant [$F_1(1,14) = 1.26$, $p > .25$; $F_2(1,16) = 4.30$, $p = .054$]. The frequency × predictability interaction was not significant in any measure (all $F$s $< 1$). Finally, there was no effect of word skipping between conditions (all $F$s $< 1$).

We ran E-Z Reader 7 (multiplicative version), using the specifications of the 20-word target set. FFD, GD, and PrSkip values predicted by the model are presented in Table 4. Whereas our observed data revealed additive effects of frequency and predictability, the predictions of the model showed an interactive pattern with a larger predictability effect for LF than for HF words in both FFD and GD. Although Rayner et al. (2004) had not observed a significant frequency × predictability interaction, they argued that there was a hint of an interactive pattern in GD, because the frequency effect was 6 msec greater for LP than for HP words, a pattern consistent with the initial, multiplicative version of E-Z Reader 7.

Rayner et al. (2004), however, modified the model so that frequency and predictability combined in an additive, rather than multiplicative, fashion. This extended, additive version of E-Z Reader 7 successfully captured the additive effects of frequency and predictability that they had observed in GD. We ran this extended, additive version in order to compare its predictions with our observed data (see Table 4).[5] This simulation performed better than the multiplicative version. However, the predicted GD values were much shorter and the frequency effect was much smaller than those for the observed data (see Table 4).

To obtain a better fit, we changed the parameters of the extended, additive version of E-Z Reader 7. The fitting index, or root-mean squared deviation (RMSD), is a function of GD, as well as skipping probability. Because the skipping probability was very low in our study, we did not use it in calculating the RMSD.[6] The resulting fit, however, produced fairly high GD values (~430 msec on average). To obtain GD values of around 300 msec, as were observed, we slowed down the rate of lexical processing by changing the $\beta_1$ and $\beta_2$ parameters.[7] In this modified extended, additive version of E-Z Reader 7, the predicted GDs were closer to the observed values in comparison with the multiplicative version of the model and showed a more additive pattern of frequency and predictability (see Table 4). However, the simulated frequency effect (35 msec), although similar to what has been observed

**Table 4**
**Observed and Simulated Mean Fixation Durations (in Milliseconds) and Skipping Probabilities for 20 Target Words**

| | | LF | | HF | |
|---|---|---|---|---|---|
| Measure | Data Type | LP | HP | LP | HP |
| FFD | Observed | 280 | 254 | 229 | 200 |
| | E-Z Reader 7 (M) | 245 | 186 | 226 | 196 |
| | E-Z Reader 7 (EA) | 194 | 175 | 190 | 184 |
| | E-Z Reader 7 (ModEA) | 255 | 232 | 233 | 240 |
| GD | Observed | 362 | 345 | 291 | 249 |
| | E-Z Reader 7 (M) | 316 | 222 | 275 | 211 |
| | E-Z Reader 7 (EA) | 241 | 216 | 218 | 207 |
| | E-Z Reader 7 (ModEA) | 344 | 298 | 298 | 275 |
| PrSkip | Observed | .07 | .03 | .04 | .07 |
| | E-Z Reader 7 (M) | .11 | .27 | .13 | .19 |
| | E-Z Reader 7 (EA) | .16 | .37 | .23 | .34 |
| | E-Z Reader 7 (ModEA) | .10 | .20 | .11 | .14 |

Note—Target words were either low- or high-frequency words (LF or HF) that were either low or high predictable (LP or HP). Fixation measures include the following: FFD, first-fixation duration; GD, gaze duration; and PrSkip, probability of skipping. Data type corresponds to either observed or simulated data. Simulated data were obtained from the following models: the multiplicative (M), extended additive (EA), and modified extended additive (ModEA) versions of E-Z Reader 7.

in other studies, was smaller than that which we observed (84 msec).

In eye movement studies, frequency effects typically tend to be larger than predictability effects. In our GD data, the frequency and predictability effects were 84 and 30 msec, respectively. None of the simulations showed this pattern: 26 vs. 79 msec for E-Z Reader 7; 16 vs. 18 msec for the extended, additive version of E-Z Reader 7; and 35 vs. 35 msec for the modified extended, additive version of E-Z Reader 7. It seems that the modified extended, additive version of E-Z Reader 7, although demonstrating equivalent frequency and predictability effects, was the best fit for our data.

## DISCUSSION

We examined the combined effects of frequency and predictability in the context of a short passage of text on eye movements in the reading of French. Comparisons were made between the observed data and different simulations of the E-Z Reader model. The initial global analyses (using most words from the text) showed that E-Z Reader 7 (original, multiplicative version) fit well with the observed frequency effects, but not with the predictability effects. Specifically, predicted fixation times showed a reverse predictability effect for HF words. These inconsistencies illustrate the point that the initial parameter setting of a model designed to reflect lexical processing should not be based solely on word frequency but should also incorporate the other main variables known to influence word recognition, such as word length and contextual predictability. To this end, we selected a set of words that were matched on these properties.

We examined a subset of 20 controlled HF and LF words that were either HP or LP from the prior context. As in Rayner et al. (2004), we observed a frequency effect in all the fixation time measures. Although the mean fixation times were comparable across studies, the effect sizes in our study (FFD, 53 msec; GD, 84 msec) were much larger than those in Rayner et al. (2004; FFD, 14 msec; GD, 17 msec). This was most likely due to differences in word frequency: HF and LF words had respective frequencies of 457 and 19 per million in our study and 150 and 5 per million in Rayner et al. (2004). Thus, there was a greater disparity between frequency groups in our study. Regarding predictability, condition means were more comparable across studies. We observed a significant predictability effect only for FFD, whereas Rayner et al. (2004) observed it for all first-pass measures (FFD, SFD, and GD). This discrepancy may have arisen from the fact that Rayner et al.'s (2004) materials comprised a series of single-line sentences. It has been demonstrated, for example, that global (discourse) and local (sentence) contexts can differentially affect lexical processing (Hess, Foss, & Carroll, 1995). It is possible that contextual effects appeared (significantly) only in the earlier FFD measure in our study because context was established both globally and locally, having more time to build up and develop. Finally, as in Rayner et al. (2004), no fixation time frequency $\times$ predictability interaction was found. In terms of skipping probability, unlike Rayner et al. (2004), we observed no differences. The skipping rate was very low in all the conditions. This could be a floor effect, resulting from a more difficult text, masking potential frequency and/or predictability effects.

With respect to simulations of the 20-word data set, the original multiplicative version of E-Z Reader 7 predicted an interactive pattern with shorter fixations than those observed. Although the extended additive version produced an additive pattern of results (as was observed), adjusting the parameters in our modified, extended additive version of E-Z Reader allowed us to obtain fixation times similar to those observed. However, we were unable to simulate frequency effects as large as those observed. Most troublesome, however, was that simulated GDs in all the models showed predictability effects equivalent to or larger than frequency effects. Our data showed the reverse. Modification of the model should allow a better simulation of the data.[8]

Across all simulations, observed fixation times were underestimated (and comparably, skipping probabilities were overestimated). There are several possible explanations for why this occurred: (1) A longer passage of text (vs. single-line sentences) might promote semantic integration processes that are not simulated by the models; (2) a language other than English might have different linguistic properties (e.g., French words tend to be longer than English words); or (3) the reading speed of the sample of French readers might be slower than average. Resolving these issues can be the focus of future investigation.

In sum, we observed individual, noninteractive effects of frequency and predictability that, overall, fit well with the extended, additive version of E-Z Reader. However, it is important to specifically test the principles of a model; accurate predictions can be obtained without necessarily reflecting the underlying mechanisms of processing. We believe that the functional transparency of E-Z Reader allows it to be further modified in order to more precisely account for this and other experimental evidence.

### AUTHOR NOTE

Portions of these data were presented at the 6th European Workshop on Language Comprehension, St. Pierre d'Oléron, France (May 2004). The research reported here was supported in part by ESRC Grant RES-000-22-1442 to S.C.S. and P. J. O'Donnell. We thank Erik Reichle for providing the electronic source code for E-Z Reader 7 and Keith Rayner, Erik Reichle, Simon Liversedge, and Patrick O'Donnell for their helpful comments on an earlier version of the manuscript. Correspondence concerning this article should be addressed to S. Miellet, Department of Psychology, University of Glasgow, 58 Hillhead Street, Glasgow G12 8QB, Scotland (e-mail: miellet@psy.gla.ac.uk).

### REFERENCES

ALTARRIBA, J., KROLL, J. F., SHOLL, A., & RAYNER, K. (1996). The influence of lexical and conceptual constraints on reading mixed-language sentences: Evidence from eye fixations and naming times. *Memory & Cognition*, **24**, 477-492.

BALOTA, D. A., POLLATSEK, A., & RAYNER, K. (1985). The interaction of contextual constraints and parafoveal visual information in reading. *Cognitive Psychology*, **17**, 364-390.

EHRLICH, S. F., & RAYNER, K. (1981). Contextual effects on word perception and eye movements during reading. *Journal of Verbal Learning & Verbal Behavior*, **20**, 641-655.

ENGBERT, R., NUTHMANN, A., RICHTER, E. M., & KLIEGL, R. (2005). A dynamical model of saccade generation during reading. *Psychological Review*, **112**, 777-813.

HESS, D. J., FOSS, D. J., & CARROLL, P. (1995). Effects of global and local context on lexical processing during language comprehension. *Journal of Experimental Psychology: General*, **124**, 62-82.

HUEY, E. B. (1908). *The psychology and pedagogy of reading*. New York: Macmillan.

INHOFF, A. W. (1984). Two stages of word processing during eye fixations in the reading of prose. *Journal of Verbal Learning & Verbal Behavior*, **23**, 612-624.

JAMES, W. (1891). *The principles of psychology*. London: Macmillan.

JAVAL, L. E. (1906). *Physiologie de la lecture et de l'écriture*. Paris: Alcan.

LAVIGNE, F., VITU, F., & D'YDEWALLE, G. (2000). The influence of semantic context on initial eye landing sites in words. *Acta Psychologica*, **104**, 191-214.

MORRISON, R. E. (1984). Manipulation of stimulus onset delay in reading: Evidence for parallel programming of saccades. *Journal of Experimental Psychology: Human Perception & Performance*, **10**, 667-682.

NEW, B., PALLIER, C., FERRAND, L., & MATOS, R. (2001). Une base de données lexicales du français contemporain sur internet: LEXIQUE. *L'Année Psychologique*, **101**, 447-462.

POLLATSEK, A., REICHLE, E. D., & RAYNER, K. (2006). Tests of the E-Z Reader model: Exploring the interface between cognition and eye-movement control. *Cognitive Psychology*, **52**, 1-56.

RAYNER, K. (1998). Eye movements in reading and information processing: 20 years of research. *Psychological Bulletin*, **124**, 372-422.

RAYNER, K., ASHBY, J., POLLATSEK, A., & REICHLE, E. D. (2004). The effects of frequency and predictability on eye fixations in reading: Implications for the E-Z Reader model. *Journal of Experimental Psychology: Human Perception & Performance*, **30**, 720-732.

RAYNER, K., BINDER, K. S., ASHBY, J., & POLLATSEK, A. (2001). Eye movement control in reading: Word predictability has little influence on initial landing positions in words. *Vision Research*, **41**, 943-954.

RAYNER, K., & DUFFY, S. A. (1986). Lexical complexity and fixation times in reading: Effects of word frequency, verb complexity, and lexical ambiguity. *Memory & Cognition*, **14**, 191-201.

RAYNER, K., SERENO, S. C., & RANEY, G. E. (1996). Eye movement control in reading: A comparison of two types of models. *Journal of Experimental Psychology: Human Perception & Performance*, **22**, 1188-1200.

RAYNER, K., & WELL, A. D. (1996). Effects of contextual constraint on eye movements in reading: A further examination. *Psychonomic Bulletin & Review*, **3**, 504-509.

REICHLE, E. D., POLLATSEK, A., FISHER, D. L., & RAYNER, K. (1998). Toward a model of eye movement control in reading. *Psychological Review*, **105**, 125-157.

REICHLE, E. D., RAYNER, K., & POLLATSEK, A. (2003). The E-Z Reader model of eye movement control in reading: Comparisons to other models. *Behavioral & Brain Sciences*, **26**, 445-476.

SCHILLING, H. E. H., RAYNER, K., & CHUMBLEY, J. I. (1998). Comparing naming, lexical decision, and eye fixation times: Word frequency effects and individual differences. *Memory & Cognition*, **26**, 1270-1281.

SERENO, S. C., BREWER, C. C., & O'DONNELL, P. J. (2003). Context effects in word recognition: Evidence for early interactive processing. *Psychological Science*, **14**, 328-333.

SERENO, S. C., O'DONNELL, P. J., & SERENO, A. B. (2003). Neural plausibility and validation may not be so E-Z. *Behavioral & Brain Sciences*, **26**, 502.

SERENO, S. C., & RAYNER, K. (2000). Spelling–sound regularity effects on eye fixations in reading. *Perception & Psychophysics*, **62**, 402-409.

STANOVICH, K. E., & WEST, R. F. (1983). On priming by sentence context. *Journal of Experimental Psychology: General*, **112**, 1-36.

## NOTES

1. The participants were asked to provide the next word of the passage on a word-by-word basis. That is, after each response, they were told the "correct" word from the passage (if different from their response) and were then asked to guess the following word on the basis of the text up to that point. This procedure was repeated until the entire passage had been presented.

2. Although E-Z Reader has recently been modified (Version 9: Pollatsek et al., 2006), the core theoretical assumptions of the extended, additive version of E-Z Reader 7 (Rayner et al., 2004) that we tested remain unchanged. However, E-Z Reader 9 does use different parameter values and assumptions regarding the programming of refixations.

3. Forty words were excluded from the analysis because they were at the beginning or end of the line. Four additional words were excluded because they were the central words of a short line at the end of a page. In prior E-Z Reader simulations, measures on targets within sentences containing regressive eye movements have been excluded. Although target word first-pass fixation measures (FFD, SFD, and GD) do not incorporate regressions (by definition), our measures did not exclude data if a regression occurred somewhere on the same line as the target. Regressive eye movements of more than five characters (excluding return sweeps at the end of lines), however, accounted for only 5.52% of all the data.

4. In the global analyses, the patterns of results for FFD and SFD were highly similar (see Tables 2 and 3). In the sample of 20 targets, FFD and SFD means were also comparable. For this reason, only FFD and GD means are reported.

5. In our rendition of the extended, additive version of E-Z Reader 7, we modified the model in order to accommodate more than one target word per line of text.

6. If skipping probability remained in the RMSD calculation, the best fit resulted in rather unrealistic fixation times of ~600 msec.

7. We used values of $\beta_1 = 250$ and $\beta_2 = 8$. All other parameters were the same as those used in Rayner et al. (2004). Their best-fitting parameter values were $\beta_1 = 218$ and $\beta_2 = 7$ for the multiplicative model and $\beta_1 = 229$ and $\beta_2 = 11$ for the extended, additive model.

8. For example, in the extended, additive version of E-Z Reader 7, the parameter alpha-3 can modulate the effect of predictability.

**APPENDIX**
**Target Words and Their English Translations**

| Condition | Item | Translation |
|---|---|---|
| LF–LP | morne | dreary |
| | hideuse | hideously |
| | singe | ape |
| | quête | quest |
| | supplice | torment |
| LF–HP | chaux | lime |
| | haleine | breath |
| | noeud | knot |
| | nourriture | food |
| | sorcière | witch |
| HF–LP | caractère | character |
| | actions | actions |
| | chambre | bedroom |
| | petite | small |
| | objet | object |
| HF–HP | fille | girl |
| | maison | house |
| | corps | body |
| | champs | fields |
| | chemin | path |

Note—Target words were either low- or high-frequency words (LF or HF) that were either low or high predictable (LP or HP).

(Manuscript received May 31, 2006;
revision accepted for publication August 14, 2006.)