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Word Recognition during Reading: The Interaction between Lexical Repetition and Frequency

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Abstract

Memory studies utilizing long-term repetition priming have generally demonstrated that priming is greater for low-frequency words than for high-frequency words and that this effect persists if words intervene between the prime and the target. In contrast, word-recognition studies utilizing masked short-term repetition priming typically show that the magnitude of repetition priming does not differ as a function of word frequency and does not persist across intervening words. We conducted an eye-tracking while reading experiment to determine which of these patterns more closely resembles the relationship between frequency and repetition during the natural reading of a text. Frequency was manipulated using proper names that were high-frequency (e.g., *Stephen*) or low-frequency (e.g., *Dominic*). The critical name was later repeated in the sentence, or a new name was introduced. First-pass reading times and skipping rates on the critical name revealed robust repetition-by-frequency interactions such that the magnitude of the repetition-priming effect was greater for low-frequency names than for high-frequency names. In contrast, measures of later processing showed effects of repetition that did not depend on lexical frequency. These results are interpreted within a framework that conceptualizes eye-movement control as being influenced in different ways by lexical- and discourse-level factors.

Efforts to understand how word repetition facilitates lexical processing have been prominent in the development of general cognitive models of both memory and word recognition. Memory studies have typically utilized tasks that demonstrate *long-term repetition priming*. For example, participants might be given a list of words to study and then later have to perform a lexical decision task where some words are repeated from the study phase. Responses tend to be faster to the repeated words than the new words—an effect that can last for hours or even days (e.g., Scarborough, Cortese, & Scarborough, 1977). In contrast, word-recognition studies have typically utilized tasks that demonstrate *short-term repetition priming*. In these tasks, a prime word is flashed very briefly and is immediately followed by a target word. Even though participants do not notice the prime, responses to the target tend to be faster when it is the same word as the prime (e.g., Forster & Davis, 1984).

Traditionally, long-term and short-term repetition priming have been treated as different phenomena that should be explained in different ways. Long-term priming effects, as studied in relation to implicit memory, have typically been explained as resulting from creation during the study phase of distinct perceptual representations in episodic memory that later contribute to the enhanced identification of repeated items in the test phase (Jacoby, 1983; Jacoby & Dallas, 1981; Roediger & Blaxton, 1987; Schacter, 1990; Tulving & Schacter, 1990; see Tenpenny, 1995 for a review). In contrast, short-term priming tasks, which are designed to better understand the very early stages of word identification, tend to assume that episodic memory and other strategic processes do not play a role in masked

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priming effects. Instead, the briefly presented prime is believed to cause a temporary change in the basic mechanisms of word recognition that leads to more efficient processing of the target if there is a relationship between the prime and the target (Evett & Humphreys, 1981; Forster, 1998, 1999; Forster & Davis, 1984, 1991). More recently, the notion that long-term and short-term priming phenomena reflect distinct cognitive mechanisms has been called into question. On one account, it has been suggested that both types of repetition priming can be explained in terms of episodic retrieval mechanisms (Bodner & Masson, 2001; Masson & Bodner, 2003). On another account, it has been argued that the priming effects in question are more consistently associated with abstract orthographic-lexical characteristics of the stimuli than with episodic representations (Bowers, 2000), although priming at the level of abstract orthographic characteristics may only occur for low-frequency words (see Vriezen, Moscovitch, & Bellos, 1995; cf. Bowers & Turner, 2003).

Tasks that measure long-term versus short-term priming tend to produce several different patterns of results, which have contributed to the development of distinct theoretical accounts of repetition priming in the memory and word-recognition literatures. Two differences that we focus on here are effects of word frequency and the presence of intervening items between the prime and the target. Memory studies utilizing long-term priming typically demonstrate a larger repetition-priming effect for low-frequency words compared to high-frequency words—an effect that persists even if other words intervene between the prime and the target (Coane & Balota, 2010; Duchek & Neely, 1989; Jacoby & Dallas, 1981; Norris, 1984; Scarborough et al., 1977; Young & Rugg, 1992). Within a memory framework, the ease of recognizing a word is typically thought to depend on the accumulation of a lifetime of encounters with that word. The difference in priming for high- versus low-frequency words occurs because high-frequency words have been encountered so often over a lifetime that a single additional episode of encountering a high-frequency word in an experiment is unlikely to influence its already easily accessible representation. In contrast, encountering a low-frequency word is much more likely to produce a distinct memory trace that can easily be retrieved when that word is presented again later in the experiment (see, e.g., Jacoby, 1983; Kirsner & Speelman, 1996; Monsell, 1985; Reder, Nhouyvanisvong, Schunn, Ayers, Angstadt, & Hiraki, 2000; Whittlesea & Jacoby, 1990).

In contrast to the general patterns observed in long-term priming, word-recognition studies utilizing short-term priming typically show that the magnitude of repetition priming does not differ as a function of word frequency, and that there is no repetition priming effect at all if visible words intervene between the prime and the target (Bodner & Masson, 1997; Ferrand, Grainger, & Segui, 1994; Forster & Davis, 1984; Holcomb & Grainger, 2007; Rajaram & Neely, 1992; Segui & Grainger, 1990; cf. Bodner & Masson, 2001; Kinoshita, 2006; see Forster, 2009, for evidence that short-term repetition priming does persist across one visible intervenor under very specific circumstances). This absence of a repetition-by-frequency interaction has contributed to the development of Forster's entry-opening model of masked priming (Forster, 1999; Forster, Mohan, & Hector, 2003; Forster, 2009). Under this model, the briefly presented prime acts to "open" the lexical representation of the word. This facilitates lexical processing of a repeated word because the necessary step of opening the word's representation has already been completed. Importantly, this model proposes that frequency effects operate independently from repetition effects during word recognition. That is, the time required to search the lexicon for low-frequency words will always be longer compared to high-frequency words; however, when the entry is found, information can be more quickly extracted if its representation has already been opened by the prime.

In sum, studies of long-term repetition priming have found that priming effects are greater for low- than for high-frequency words, and this effect persists across intervening words. In contrast, studies of short-term repetition priming have typically found that priming effects do not differ as a function of word frequency and no priming is obtained if visible words intervene between the prime and the target. Importantly, both types of priming experiments have typically presented stimuli as a series of isolated words—either as part of a list-learning paradigm or in a situation where the prime is masked and the target requires an overt response.

In this paper, we take a different approach by using eye-tracking to investigate the nature of the relationship between word frequency and repetition during the natural reading of a text. Previous experiments using this methodology have provided a great deal of evidence that reading is influenced by both word frequency and word repetition, but very little evidence about their joint effects. Many eye-tracking studies have shown that high-frequency words are processed more quickly and more easily than low-frequency words as measured by first-pass reading times (e.g., Inhoff & Rayner, 1986; Rayner & Duffy, 1986; see Rayner, 1998 for a review), the probability of first-pass word skipping (e.g., Henderson & Ferreira, 1993; Rayner, Sereno, & Raney, 1996), and spillover effects on the following word (e.g., Rayner & Duffy, 1986; Rayner, Sereno, Morris, Schmauder, & Clifton, 1989). These robust effects of word frequency on eye-movement measures of early language processing have been central to the development of theoretical accounts of the coordination of word-recognition and oculomotor processes during reading. More recent studies have demonstrated that lexical frequency also plays a role in higher-level sentence processing, influencing the time course of integrating information between more than one clause in syntactically complex sentences (Johnson, Lowder, & Gordon, 2011; Tily, Fedorenko, & Gibson, 2010). Similarly, eye-movement studies have shown that repetition priming facilitates word recognition, as measured by first-pass reading times (e.g., Choi & Gordon, 2012; Gordon, Plummer, & Choi, 2012; Ledoux, Camblin, Swaab, & Gordon, 2007; Liversedge, Pickering, Clayes, & Branigan, 2003; Traxler, Foss, Seely, Kaup, & Morris, 2000). In addition, language-comprehension processes change between the first reading of a text and its subsequent rereading. These studies have generally shown large processing advantages during the second reading (e.g., Carr, Brown, & Charalambous, 1989; Hyona & Niemi, 1990; Levy & Burns, 1990; Raney & Rayner, 1995; Sheridan & Reingold, 2012). In particular, Raney and Rayner examined the influence of word frequency on text rereading, demonstrating that frequency and repetition had additive effects on eye-movement measures, but that there was no interaction between these two factors.

In this experiment, we manipulated lexical frequency and repetition using proper names in a single sentence, as shown in Example 1. Proper names were used as the critical words because they can easily be placed in two locations in the same sentence while also fully counterbalancing the names in new and repeated conditions. This level of experimental control would be nearly impossible to achieve if content words had been used instead of proper names, because content words have stronger lexical-semantic constraints that often make it difficult to repeat them felicitously in a single sentence and to separate repetition effects from effects of semantic congruence in relation to other meanings in the sentence. In 1a and 1b, the target words are high-frequency names (i.e., *Charles* and *Stephen*), whereas in 1c and 1d, the target words are low-frequency names (i.e., *Dominic* and *Forrest*). These names are repeated from earlier in the sentence in 1a and 1c, and they are new in 1b and 1d. Note that the sentence subject in these materials was always conjoined (e.g., *Charles and Dustin*), so that repetition of a name later in the sentence was felicitous and would not result in a repeated-name penalty (Gordon, Grosz, & Gilliom, 1993).

1.

a. High-frequency name/Repeated

In spite of the rain Charles and Dustin enjoyed the concert at which Charles met the band.

b. High-frequency name/New

In spite of the rain Charles and Dustin enjoyed the concert at which Stephen met the band.

c. Low-frequency name/Repeated

In spite of the rain Dominic and Dustin enjoyed the concert at which Dominic met the band.

d. Low-frequency name/New

In spite of the rain Dominic and Dustin enjoyed the concert at which Forrest met the band.

Substantial similarities have been found in the initial recognition of proper names and common nouns. Valentine, Bredart, Lawson, and Ward (1991) demonstrated that naming latencies for proper names follow a similar pattern as do naming latencies for common nouns— that is, onset to begin speaking is faster for high-frequency names compared to low-frequency names. Additional research has shown that when participants make familiarity judgments to proper names (e.g., *David Steel*), later performance on a lexical-decision task is facilitated if the surname is repeated as a common noun (e.g., *steel*), and the effect can be reversed such that lexical decisions to common nouns can prime familiarity decision times to proper names, suggesting that similar sorts of lexical representations are accessed by common nouns and proper names (Valentine, Moore, Flude, Young, & Ellis, 1993; see also Valentine, Moore, & Bredart, 1995). Finally, an event-related potential (ERP) study by Van Petten, Kutas, Kluender, Mitchiner, and McIsaac (1991) demonstrated that repetition of common nouns and proper names result in similar reductions in the amplitude of the N400 component, again suggesting that the lexical-retrieval processes for these two types of words share a common mechanism. Van Petten et al. did observe different repetition effects for common nouns and proper names later in the ERP waveform; however, others have pointed out that repetition of a proper name in that study often occurred with several intervening sentences appearing between the first and second presentation, which may have contributed additional difficulty (see Camblin, Ledoux, Boudewyn, Gordon, & Swaab, 2007; Ledoux et al., 2007)

The design of the current experiment allows us to determine whether the effect of lexical repetition on word recognition during reading depends on the frequency of the repeated word. In addition, eye-movement data provide information about the time course of these effects which may offer additional insight into the cognitive mechanisms that underlie lexical processing. Eye-movement patterns during reading can be separated into early first-pass measures thought to reflect word recognition and lexical access and later measures that are associated with memory-dependent processes of higher-level text integration (e.g., Clifton, Staub, & Rayner, 2007). Localizing the repetition-by-frequency interaction to early or later stages of processing would provide evidence about whether these effects are more accurately characterized as lexical-access or memory-related phenomena. Observing a repetition-by-frequency interaction in first-pass reading measures would be consistent with the interactions of word frequency and repetition priming found in long-term priming paradigms (Duchek & Neely, 1989; Jacoby & Dallas, 1981; Norris, 1984; Scarborough et al., 1977; Young & Rugg, 1992). That such interactions may at least partially reflect improvement in recognition processes, not simply changes in bias, is supported by findings that repetition priming improves sensitivity in forced-choice recognition judgments following brief presentation of low-frequency but not high-frequency words (Bowers, 1999;

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Ratcliff & McKoon, 1997; Wagenmakers, Zeelenberg, & Raaijmakers, 2000). Observing such an interaction in first-pass eye-movement measures would further show that facilitation of recognition due to repetition is particularly strong for low-frequency words, as might be the case if facilitation affected a process of lexical search that is already easy for high-frequency words. Additionally, observing dissociations between eye-movement measures of early and late processes in the effects of repetition, frequency, and their interaction would provide evidence about the relationship between lexical recognition and text integration during reading.

Method

Participants

Forty students at the University of North Carolina at Chapel Hill participated in this experiment in exchange for course credit. They were all native English speakers and had normal or corrected-to-normal vision.

Materials

Participants were presented with 40 experimental sentences and 86 filler sentences. The experimental sentences were adapted from Ledoux et al. (2007). Each sentence began with a locative phrase, and the subject of each sentence consisted of two proper names conjoined by *and*. The target word occurred later in the sentence and was either a repetition of a name from the conjoined subject or a new name (see Example 1; see Appendix for a complete list of experimental sentences). There were eight versions of each sentence, which were derived by crossing name frequency and repetition, as well as by allowing each critical name to serve as both prime and target. Name frequencies were categorized using an analysis of the names of incoming UNC freshmen over a five-year period. High-frequency names were those appearing at least 100 times, whereas low-frequency names were those that appeared four or five times[1]. The names in the conjoined subject that did not serve as a target name (e.g., *Dustin* in Example 1) were medium-frequency names, appearing between 20 and 60 times in the UNC names database. Critical names varied between five and eight characters in length. For each sentence frame, the high- and low-frequency names used for counterbalancing were matched in length. The critical word never appeared within two words of the beginning or the end of a line. One version of each item was assigned to one of eight lists such that no participant saw more than one version of each item. Each set of target names appeared in two sentence frames; however, our counterbalancing procedure ensured that no participant saw the same name in more than one sentence. After each sentence, a true/false question appeared.

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[1]Kinoshita (2006) has suggested that short-term priming studies have often failed to find a repetition-by-frequency interaction because of the specific frequency ranges that have been tested. She ran one short-term priming study with very-low-frequency words, which replicated previous findings in demonstrating no repetition-by-frequency interaction. In her second experiment, she used low-frequency words that were slightly higher in frequency, and this time found a significant interaction. To specifically test whether there was a difference in frequencies for the low-frequency names used in the current experiment and the words used by Kinoshita (2006), we computed the log-transformed occurrences per million for our low-frequency names and for Kinoshita's different classes of low-frequency words using the Corpus of Contemporary American English (COCA; Davies, 2008). There was no frequency difference between our low-frequency names (M = .51, SD = .54) and Kinoshita's *very-low-frequency* words (M = .45, SD = .38), $t < 1$; however, our low-frequency names were significantly lower in frequency than Kinoshita's *low-frequency* words (M = .98, SD = .32), $t(86) = 5.08$, $p < .001$. This demonstrates that the low-frequency names we used had similar frequencies to the very-low-frequency words used by Kinoshita. Thus, any repetition-by-frequency interaction that we observe in the current experiment cannot be discounted on the grounds that the low-frequency names we used were not low enough in frequency to be comparable to the low-frequency words that have been used in masked-priming studies, which have not shown an interaction between repetition and frequency.

Procedure

The sentences were presented on a computer screen, and eye movements were monitored using an EyeLink 1000 system (SR Research). This device records eye movements using a camera mounted on the table in front of the participant, sampling pupil location at a rate of 1000 Hz and parsing the samples into fixations and saccades. A chinrest was used to minimize head movement. At the start of the session, the eye-tracker was calibrated for each participant. At the start of each trial, a fixation point appeared on the left of the screen at the location where the first word of the sentence would subsequently be presented. The experimenter used a second computer to monitor the location and steadiness of the participant's gaze. When the participant's gaze was adequately fixated on this point, the experimenter pressed a button that caused the sentence to be presented. After reading the sentence, the participant pressed a button, which caused the sentence to disappear and a comprehension question to appear. Participants pressed one key to answer "true," and another to answer "false." After the participant responded to the comprehension question, the trial ended and the fixation point for the next trial appeared.

Each experimental session began with six filler sentences. After this warm-up block, the remaining 120 sentences were presented in a different random order for each participant. Participants were instructed to read at a natural pace.

Analysis

In our analysis of the eye-tracking data, we report four measures that are thought to assess the earliest stages of word recognition and lexical access (e.g., Clifton et al., 2007). *Skipping rate* is the proportion of trials on which a word did not receive a first-pass fixation. *Single-fixation duration* is the average of the durations of the initial, first-pass fixation on a word, provided that the word received only one first-pass fixation. *First-fixation duration* is the average of the durations of the initial, first-pass fixation on a word, regardless of the total number of first-pass fixations. *Gaze duration* is the average of the sum of all first-pass fixations on a word. In addition to these four early-processing measures, we also report two measures that reflect later stages of sentence processing. *Total time* is the sum of all fixation durations on a word or region of interest. *Rereading duration* is the difference between total time and gaze duration. An automatic procedure in the Eyelink software combined fixations that were shorter than 80 ms and within one character of another fixation into one fixation. Remaining fixations that were shorter than 120 ms or longer than 800 ms were deleted (for similar approaches, see, e.g., Drieghe, Pollatsek, Juhasz, & Rayner, 2010; Folk & Morris, 2003; Johnson, Perea, & Rayner, 2007; Rayner, Castelhano, & Yang, 2010).

We report reading times for three regions of interest: the prime, the target, and the post-target region. The *prime* was the name from the conjoined sentence subject that could be repeated later in the sentence (e.g., *Charles* or *Dominic* in Example 1). The *target* was the critical name of the sentence, which was either repeated from earlier in the sentence or was a new name (e.g., *Charles, Stephen, Dominic,* or *Forrest* in Example 1) The *post-target region* consisted of the word after the target, or the two words after the target when the word after the target had fewer than five letters (making it likely to be skipped).

Results

Mean reading times for the three regions of interest are displayed in Table 1. Across participants, mean comprehension-question accuracy was 93%.

Prime

All measures of early processing of the prime provided evidence that high-frequency words were easier to process than low-frequency words. Although the effect was only marginally significant for skipping rates, $F_1(1,39) = 3.12$, $p < .10$; $F_2(1, 39) = 4.48$, $p < .05$, it was highly significant for all three reading-time measures: single-fixation duration, $F_1(1,39) = 13.36$, $p < .005$; $F_2(1, 39) = 15.90$, $p < .001$, first-fixation duration, $F_1(1,39) = 14.15$, $p < .005$; $F_2(1, 39) = 20.66$, $p < .001$, and gaze duration, $F_1(1,39) = 32.33$, $p < .001$; $F_2(1, 39) = 33.67$, $p < .001$. This pattern of effects thus validates our methodology for selecting high- and low-frequency names as stimuli.[2]

The main effect of frequency on the prime persisted into later measures, again showing longer reading times on low-frequency names than high-frequency names. The effect was significant in rereading (for the subjects analysis only), $F_1(1,39) = 5.86$, $p < .05$; $F_2(1, 39) = 2.22$, $p > .10$, and in total time, $F_1(1,39) = 20.05$, $p < .001$; $F_2(1, 39) = 9.63$, $p < .005$. In addition, there was an effect of repetition on later measures such that primes had shorter reading times when they were later repeated in the sentence than when a new name was introduced. This main effect was marginally significant in rereading, $F_1(1,39) = 2.87$, $p < .10$; $F_2(1, 39) = 3.57$, $p < .07$ and fully significant in total time. $F_1(1,39) = 4.17$, $p < .05$; $F_2(1, 39) = 6.62$, $p < .05$. Neither measure showed any hint of a repetition-by-frequency interaction (all *F*s < 1).

Target

At the target, there was evidence of repetition priming, such that repeated names were processed more quickly than new names. This main effect of repetition was observed for all reading-time measures: single-fixation duration, $F_1(1,39) = 10.35$, $p < .005$; $F_2(1, 39) = 9.14$, $p < .005$; first-fixation duration, $F_1(1,39) = 12.21$, $p < .005$; $F_2(1, 39) = 12.41$, $p < .005$; gaze duration, $F_1(1,39) = 15.78$, $p < .001$; $F_2(1, 39) = 12.01$, $p < .005$; rereading, $F_1(1,39) = 30.81$, $p < .001$; $F_2(1, 39) = 11.20$, $p < .005$; and total time, $F_1(1,39) = 40.28$, $p < .001$; $F_2(1, 39) = 21.24$, $p < .001$. There was also a significant repetition-priming effect on skipping rates, such that repeated names were more likely to be skipped than new names, $F_1(1,39) = 8.45$, $p < .01$; $F_2(1, 39) = 7.34$, $p < .02$. The main effect of frequency, which had been observed for the primes, persisted weakly for the targets, with marginally significant effects on gaze duration (in the subjects analysis), $F_1(1,39) = 4.09$, $p < .05$; $F_2(1, 39) = 1.75$, $p > .15$, and on single-fixation duration, $F_1(1,39) = 3.40$, $p < .08$; $F_2(1, 39) = 4.27$, $p < .05$. High-frequency names were significantly more likely to be skipped than low-frequency names, $F_1(1,39) = 6.69$, $p < .02$; $F_2(1, 39) = 5.25$, $p < .05$. The main effect of frequency was not significant in later-processing measures.

Critically, the main effects of repetition and frequency were qualified by significant repetition-by-frequency interactions on all measures of early processing: skipping rates, $F_1(1,39) = 5.52$, $p < .05$; $F_2(1, 39) = 5.47$, $p < .05$; single-fixation duration, $F_1(1,39) = 5.11$, $p < .05$; $F_2(1, 39) = 5.55$, $p < .05$; first fixation duration, $F_1(1,39) = 6.70$, $p < .02$; $F_2(1, 39) =$

[2]We also conducted a more fine-grained analysis of name frequency and reading time, comparing our UNC names corpus with two other corpora: SUBTLEXus (Brysbaert & New, 2009) and COCA (Davies, 2008). We compiled frequency information for the two names that appeared as the conjoined subject in each of our sentences (a total of 120 unique names). As discussed in the Methods section, these were chosen from the UNC names corpus to be high-frequency (100 tokens or more), medium-frequency (between 20 and 60 tokens), and low-frequency (4 or 5 tokens). All of these names also appeared in COCA; however, only 52% of them appeared in SUBTLEXus with many of the names that had very high frequencies in the UNC names corpus not appearing at all in SUBTLEXus (e.g., *Amanda*, *Ashley*, *Jennifer*, *Jessica*, *Justin*). We correlated gaze duration on these names with the log-transformed frequency information from each of the three corpora, obtaining the following results: UNC corpus ($r = -.44$, $p < .001$); SUBTLEXus ($r = -.16$, *ns*); COCA ($r = -.34$, $p < .001$). Thus, although all corpora showed a tendency for high-frequency names to be processed more quickly than low-frequency names, the relationship was only significant in the UNC corpus and COCA, with the relationship being strongest in the UNC corpus.

5.79, $p < .05$; and gaze duration, $F_1(1,39) = 6.17$, $p < .02$; $F_2(1, 39) = 9.88$, $p < .005$. Follow-up contrasts revealed that the source of the interaction was the same across all four of these measures. That is, the Low Frequency-New condition produced longer reading times and lower skipping rates than both the Low Frequency-Repeated condition and the High Frequency-New condition (all *t*s > 2.0, all *p*s < .05). In contrast, there was no difference in processing difficulty between the High Frequency-New condition and the High Frequency-Repeated condition, and no difference between the High Frequency-Repeated condition and the Low Frequency-Repeated condition (all *t*s < 1.7, all *p*s > .10).

The repetition-by-frequency interaction also emerged in total time, $F_1(1,39) = 4.37$, $p < .05$; $F_2(1, 39) = 5.40$, $p < .05$. As with the early-processing measures, the follow-up contrasts for total time revealed a strong repetition effect for low-frequency names, $t_1(39) = 5.64$, $p < .001$; $t_2(39) = 5.02$, $p < .001$. However, unlike the early-processing measures, there was also a repetition effect for high-frequency names (significant in the subjects analysis), $t_1(39) = 2.54$, $p < .05$; $t_2(39) = 1.60$, $p > .10$. For rereading, there was no indication of a repetition-by-frequency interaction, $F_1(1,39) < 1$; $F_2(1, 39) < 1$.

Post-Target Region

Skipping rates, first-fixation duration, and single-fixation duration were not analyzed for this region because this region often consisted of two words, which limits the interpretability of these measures. Analysis of gaze duration on this region produced no significant main effects or interactions (all *F*s < 1). In contrast, measures of later processing revealed a main effect of repetition on the post-target region such that times were shorter following a repeated name than a new name. The effect was significant for rereading (marginal in the items analysis), $F_1(1,39) = 8.03$, $p < .01$; $F_2(1, 39) = 3.58$, $p < .07$, and fully significant for total time, $F_1(1,39) = 10.66$, $p < .005$; $F_2(1, 39) = 7.43$, $p < .01$. There were no significant main effects of frequency or repetition-by-frequency interactions in either of these later-processing measures.

The primary results can be summarized as follows. Eye-tracking measures reflecting early stages of word-recognition produced an interaction between repetition and frequency on the target word itself such that low-frequency words benefited from repetition but high-frequency words did not. In contrast, measures reflecting later stages of sentence interpretation revealed repetition-priming effects on rereading of the prime, the target, and the region after the target that in general did not depend on frequency.

Discussion

This experiment demonstrated greater repetition priming on first-pass eye-movement measures of reading for low-frequency words than for high-frequency words presented in sentences where several words intervened between the first (prime) and second (target) presentation of the word. These first-pass reading measures (skipping, first-fixation duration, single-fixation duration, and gaze duration) are very sensitive to factors associated with the ease of recognizing words (Rayner, 1998) and are considered valid measures of word recognition processes by current theories of eye-movement control during reading (Clifton et al., 2007). This pattern differs from that found in Raney and Rayner’s (1995) rereading study, where frequency and repetition had additive rather than interactive effects on eye-movement measures. However, in contrast to the within-sentence word repetition paradigm used here, processing facilitation in the rereading paradigm reflects not only the effects of repeating the target word but also of processing that word a second time in exactly the same sentence context. The interaction observed here between repetition and frequency is consistent with the pattern observed in the memory literature where long-term repetition priming effects are typically greater for low-frequency words than for high-frequency

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words, with this effect persisting across intervening words (e.g., Scarborough et al., 1977). Our results are inconsistent with the pattern observed in the majority of studies in the word-recognition literature where short-term repetition priming typically does not differ as a function of word frequency and does not persist if other words intervene between the prime and the target (e.g., Forster & Davis, 1984; cf. Forster, 2009).

Research on repetition priming has sought to answer questions related to both word-recognition and memory processes. The use of eye-tracking during reading offers new ways of isolating and characterizing the effects of repetition on these two processes. Figure 1 sketches a model of how different levels of linguistic representation influence eye movements during reading, integrating common features of models for eye-movement control during reading, such as E-Z Reader (Pollatsek, Reichle, & Rayner, 2006) and SWIFT (Engbert, Nuthmann, Richter, & Kliegl, 2005), with the model of discourse and coreference processing proposed by Gordon and Hendrick (1998). It is generally accepted that the characteristics of eye movements during first-pass reading are influenced both by oculo-motor constraints and word recognition processes, though models differ in their characterizations of the relative contributions of word-recognition (Pollatsek et al., 2006) versus oculo-motor (Engbert et al., 2005) processes. The target words in the current experiment were matched in length and appeared in the same position, surrounded by the same words so that differences across the frequency and repetition conditions depend on ease of word recognition without influence from oculo-motor factors. The timing of a saccade from a fixation on a word is influenced by recognition of that word (see Engbert et al., 2005 and Pollatsek et al., 2006 for detailed discussions) so that the durations of first-pass fixations are shorter when a word is recognized easily, as would be the case if it were high frequency or had been encountered recently. The model in Figure 1 allows for these effects through the connection from lexical processing to oculo-motor control processes. Because first-pass eye-movement measures are thought to reflect this influence of word recognition on oculo-motor control, we interpret the repetition-by-frequency interaction observed here for first-pass measures as showing that lexical repetition facilitates the process of *recognizing* low-frequency words, whereas repetition does not appear to benefit the process of recognizing high-frequency words.

While basic word recognition goes on, the effort to understand the meaning of a sentence or short discourse leads to the construction of a discourse model that represents patterns of reference and coreference and which captures the predicate-argument relationships described in the text (Gordon & Hendrick, 1998, among others). In our view the discourse model is an episodic memory structure of the sort that Ericsson and Kintsch (1995) call *long-term working memory* (LTWM). LTWM is an effective form of working memory for language comprehension because it is richly encoded such that the ongoing task of comprehension provides cues for the fast retrieval of needed information and the results of incremental comprehension modify the episodic representation so that it captures the developing meaning of the discourse. Conceiving of working memory as a form of episodic, long-term memory rather than as a capacity-limited, temporary form of memory provides a natural way of explaining the robustness of language comprehension and other skilled performances in the face of interruptions that would cause disruption of temporary memories that must be maintained through operations such as rehearsal (Ericsson & Kintsch, 1995; Ledoux & Gordon, 2006; see Gordon & Lowder, 2012 for a review of evolving notions of working memory in language comprehension). Experimental results have shown that effects of discourse processing on eye movements (Figure 1) are delayed relative to effects on word recognition and that they are distributed more broadly. In particular, Ledoux et al. (2007) investigated repetition priming for proper names in sentences where the target word was used felicitously with respect to the broader sentence context (e.g., *At the office Daniel and Amanda moved the cabinet because DANIEL needed* *room for the desk*) or infelicitously (e.g., *At the office Daniel moved the cabinet because DANIEL needed room for the desk*). First-pass reading times showed nearly identical repetition priming at the second occurrence of *Daniel*, as compared to a new name, with greater difficulty for the infelicitous repetition condition emerging on later measures of rereading for a region following the target word. These measures also showed evidence of disrupted processing for the sentences with new names—a pattern that was taken to reflect the difficulty of representing three rather than two named individuals in the discourse model. The current experiment also provides evidence of difficulty in later processing of new as compared to repeated names. In contrast to the first-pass measures, this effect is seen both for high-frequency and low-frequency names, a finding that is consistent with the idea that it is more difficult to accurately represent the interrelations of three characters than two. Unlike its effect on word recognition, this discourse-level effect of repetition/novelty depends little or not at all on the frequency of the critical word.

Explanations within the memory literature regarding the mechanisms responsible for repetition-priming effects have tended to endorse the notion that initial processing of a word creates a distinct perceptual representation that is retrieved from episodic memory to facilitate processing of the word when it is encountered a second time (e.g., Jacoby, 1983; Jacoby & Dallas, 1981; Roediger & Blaxton, 1987; Schacter, 1990; Tulving & Schacter, 1990; see Tenpenny, 1995 for a review). The notion that episodic memory plays an active role during the early stages of word recognition differs considerably from our model, where episodic memory is proposed to be involved in the higher-level role of text integration and maintaining representations of various discourse entities. Although the repetition-by-frequency interaction we observed on first-pass eye-tracking measures is consistent with previous findings in studies utilizing long-term priming, we do not believe that the interactive effect we observed here is being mediated by episodic memory, as these eye-tracking measures are thought to reflect the earliest stages of word recognition rather than processes that tap into memory (e.g., Clifton et al., 2007). Indeed, the reading-time patterns observed here occurred much more rapidly after fixation of the critical word than the lexical-decision responses that are typically collected in repetition-priming studies; gaze duration measures showing the repetition-by-frequency interaction averaged about 195 ms (see Table 1), whereas lexical-decision times showing this effect tend to be in the range of 500 to 700 ms (Coane & Balota, 2010; Forster & Davis, 1984; Scarborough et al., 1977). We believe that the very short latencies of these eye-tracking measures justify the assumption that they reflect rapid processes of word recognition (see also Rayner, 1998) rather than post-recognition processes such as the metalinguistic judgment required by the lexical decision task where performance may reflect contributions of a repetition-by-frequency interaction at the level of subjects' confidence in addition to early perceptual stages (Balota & Chumbley, 1984). In contrast, the main effects of repetition seen in later eye-tracking measures of rereading duration and total time on the prime, the target, and the region after the target did not depend on frequency. Indeed, we propose that these measures reflect language-comprehension processes that occur at a discourse-level of representation, where episodic memory must be accessed to keep track of the various characters introduced by the sentence. The greater rereading durations and total times for new versus repeated names—irrespective of the lexical-level manipulation of frequency—thus reflects the difficulty that readers experience in keeping track of all three names at once.

As discussed previously, the repetition effects found with long-term priming methods are at least in part the result of increased sensitivity in word identification as shown by recognition accuracy in forced-choice tasks, and this increased sensitivity is especially strong for low-frequency words (Bowers, 1999; Wagenmakers et al., 2000). This effect of repetition on perceptual sensitivity conflicts with earlier work proposing that repetition priming can be explained entirely in terms of *bias* such that exposure to a word reduces the amount of perceptual evidence needed to identify the word on a subsequent occasion (Morton, 1979; Ratcliff & McKoon, 1997). Gordon et al. (2012) also provided evidence that within-sentence repetition priming involves more than changes in bias by showing that the increased skipping rate for repeated target words is not found when the target word is presented in the parafovea as a transposed-letter (TL) nonword derived from the target (e.g., *Hreman* instead of *Herman*). If processing of the prime reduced the amount of evidence needed to trigger recognition of the target, then increased skipping should have been found not only when the letter string in the parafovea was the target (*Herman*), but also when it was the highly similar TL nonword (*Hreman*). The specificity of the repetition-priming effect in skipping rates indicates that priming did not simply involve a criterion adjustment but also a change in sensitivity (Gordon et al., 2012; see also Choi & Gordon, 2012; under review). The current study provides further evidence that this increase in sensitivity is greater for low-frequency than high-frequency words.

Given that the first-pass eye-tracking measures reported here reflect early stages of word recognition, one might have predicted that they would follow the same pattern observed in word-recognition studies utilizing short-term priming in showing only additive effects of repetition and frequency and no interaction. Instead, the interaction we observed on early measures using within-sentence lexical repetition priming with intervening words cannot be explained by priming mechanisms advanced in the masked-priming literature, such as temporary opening of a lexical entry (Forster et al., 2003) or build-up of activation along the path of orthographic-to-lexical representations (Grainger & Jacobs, 1996, 1999), as both of these explanations assume that recognition of words that intervene between the prime and the target undo any priming benefit that would be observed if the target immediately followed the prime. Instead, we propose that repetition facilitates search for the correct lexical entry—a process that is already easy for high-frequency words. Of course it is possible that multiple types of priming operate during reading and that different types of processes underlie the priming that is observed when there are intervening words and when there are not. One argument in favor of serial attention-shifting models of eye-movement control during reading (Pollatsek et al. 2006; Reichle, Pollatsek, Fisher, & Rayner, 1998; see also Gordon et al., 2012) is that they provide an inherent limitation on the kinds of priming that might take place between different words in a sentence. In general, priming between different words in a sentence at the orthographic or phonological level will not facilitate accurate word recognition because typically the orthographic/phonological patterns of one word in a sentence do not provide evidence about the identity of different words in the sentence. The resetting mechanisms posited to account for the elimination of masked priming by visible intervening words (e.g., Forster et al., 2003; Grainger & Jacobs, 1996) would also serve to eliminate dependencies in the recognition of different words in a sentence—dependencies that are more likely to interfere with recognition than facilitate it. The most obvious role for short-term priming mechanisms for word recognition during sentence reading occurs in the case of parafoveal preview benefit (Henderson & Ferreira, 1990; Kennison & Clifton, 1995; White, Rayner, & Liversedge, 2005), which is observed when lexical processing begins on a letter string in the parafovea before that string is fixated in the fovea. Indeed, it is in such cases where impressive parallels in patterns of priming have been found between masked-priming and eye-tracking measures (e.g., Johnson et al., 2007; Perea & Lupker, 2003).

The current results add to previous demonstrations (e.g., Gordon et al., 2012; Ledoux et al., 2007; Liversedge et al., 2003; Traxler et al., 2000) that lexical repetition priming also occurs between different words in the same sentence and extend the parallel between such priming and the repetition-priming effects that are observed in memory studies: both effects persist across intervening words and interact with lexical frequency. This pattern is most readily explained in terms of how priming affects the ease of finding a word in the mental lexicon, with difficult-to-find, low-frequency words having the most room to benefit from having been found recently.

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Appendix

Appendix:

Within each set of items the first sentence shows the high-frequency names, whereas the second sentence shows the low-frequency names.

1. Last week Kristina and {Jennifer/Kimberly} joined protests against the tuition hike because {Jennifer/Kimberly} could not afford the new rate.

   Last week Kristina and {Catalina/Clarissa} joined protests against the tuition hike because {Catalina/Clarissa} could not afford the new rate.

2. Despite the weather {Jennifer/Kimberly} and Stefanie went to the beach when {Jennifer/Kimberly} rented a house for a week.

   Despite the weather {Catalina/Clarissa} and Stefanie went to the beach when {Catalina/Clarissa} rented a house for a week.

3. Over the summer {Jessica/Rebecca} and Jillian drove to the lake so that {Jessica/Rebecca} could go swimming.

   Over the summer {Harriet/Roxanne} and Jillian drove to the lake so that {Harriet/Roxanne} could go swimming.

4. After taking a loan Barbara and {Jessica/Rebecca} started a business when {Jessica/Rebecca} finished college.

   After taking a loan Barbara and {Harriet/Roxanne} started a business when {Harriet/Roxanne} finished college.

5. Yesterday evening Maria and {Emily/Sarah} went to see a movie after {Emily/Sarah} described the review from the newspaper.

   Yesterday evening Maria and {Greta/Lynne} went to see a movie after {Greta/Lynne} described the review from the newspaper.

6. Last July Erika and {Emily/Sarah} put on a yard sale because {Emily/Sarah} had made money with one the year before.

   Last July Erika and {Greta/Lynne} put on a yard sale because {Greta/Lynne} had made money with one the year before.

7. Understandably {Ashley/Lauren} and Claire left the party early after {Ashley/Lauren} made a rude comment at dinner.

   Understandably {Aubrey/Felice} and Claire left the party early after {Aubrey/Felice} made a rude comment at dinner.

8. With great care {Ashley/Lauren} and Joanna painted the living room while {Ashley/Lauren} was on vacation from work.

   With great care {Aubrey/Felice} and Joanna painted the living room while {Aubrey/Felice} was on vacation from work.

9. With patience Stacey and {Amanda/Rachel} waited for the landlord to cool down after {Amanda/Rachel} had a fight with him.

With patience Stacey and {Moriah/Selena} waited for the landlord to cool down after {Moriah/Selena} had a fight with him.

10. Quite spontaneously Martha and {Amanda/Rachel} got married when {Amanda/Rachel} lived in Washington.

Quite spontaneously Martha and {Moriah/Selena} got married when {Moriah/Selena} lived in Washington.

11. At the mall {Laura/Megan} and Stacy shopped for tents before {Laura/Megan} went camping.

At the mall {Janel/Naomi} and Stacy shopped for tents before {Janel/Naomi} went camping.

12. At the press conference {Laura/Megan} and Jesse predicted an amazing season after {Laura/Megan} recruited the star player.

At the press conference {Janel/Naomi} and Jesse predicted an amazing season after {Janel/Naomi} recruited the star player.

13. Out in the field Chelsea and {Kristen/Melissa} set up the telescope before {Kristen/Melissa} started looking at the moon.

Out in the field Chelsea and {Celeste/Chandra} set up the telescope before {Celeste/Chandra} started looking at the moon.

14. At the station {Kristen/Melissa} and Rebekah waited nervously after {Kristen/Melissa} announced the train was late.

At the station {Celeste/Chandra} and Rebekah waited nervously after {Celeste/Chandra} announced the train was late.

15. At about noon {Heather/Lindsay} and Carolyn turned onto a side road because {Heather/Lindsay} warned of the dangerous highway.

At about noon {Belinda/Marilyn} and Carolyn turned onto a side road because {Belinda/Marilyn} warned of the dangerous highway.

16. Every week Candace and {Heather/Lindsay} went to the theater because {Heather/Lindsay} gave free acting lessons.

Every week Candace and {Belinda/Marilyn} went to the theater because {Belinda/Marilyn} gave free acting lessons.

17. By chance Caitlin and {Allison/Tiffany} had been staying at the beach when {Allison/Tiffany} won the surfing contest.

By chance Caitlin and {Addison/Cecelia} had been staying at the beach when {Addison/Cecelia} won the surfing contest.

18. On the camping trip {Allison/Tiffany} and Abigail brought the insect repellent because {Allison/Tiffany} was allergic to bug bites.

On the camping trip {Addison/Cecelia} and Abigail brought the insect repellent because {Addison/Cecelia} was allergic to bug bites.

19. With reluctance {Julia/Kelly} and Molly washed the dishes while {Julia/Kelly} talked about the upcoming election.

With reluctance {Mindy/Tasha} and Molly washed the dishes while {Mindy/Tasha} talked about the upcoming election.

20. At the campground Robin and {Julia/Kelly} cooked the hotdogs as soon as {Julia/Kelly} started the fire.

At the campground Robin and {Mindy/Tasha} cooked the hotdogs as soon as {Mindy/Tasha} started the fire.

21. Each night Kenneth and {Matthew/Michael} drove downtown because {Matthew/Michael} was performing with the symphony orchestra.

Each night Kenneth and {Bernard/Carlton} drove downtown because {Bernard/Carlton} was performing with the symphony orchestra.

22. In truth Raymond and {Matthew/Michael} often talked on the telephone when {Matthew/Michael} visited other states.

In truth Raymond and {Bernard/Carlton} often talked on the telephone when {Bernard/Carlton} visited other states.

23. Despite the distance {David/James} and Henry looked for a house near the college after {David/James} was mugged downtown.

Despite the distance {Clark/Edgar} and Henry looked for a house near the college after {Clark/Edgar} was mugged downtown.

24. Using the cage Grant and {David/James} trapped the snake so {David/James} could transport it to a safe habitat.

Using the cage Grant and {Clark/Edgar} trapped the snake so {Clark/Edgar} could transport it to a safe habitat.

25. According to the memo Graham and {Andrew/Robert} had plans to research the subject before {Andrew/Robert} wrote up the proposal.

According to the memo Graham and {Cedric/Darren} had plans to research the subject before {Cedric/Darren} wrote up the proposal.

26. For a long time Ronald and {Andrew/Robert} worried about burglary after {Andrew/Robert} saw the report on property crime.

For a long time Ronald and {Cedric/Darren} worried about burglary after {Cedric/Darren} saw the report on property crime.

27. Last Friday {Benjamin/Jonathan} and George left work early after {Benjamin/Jonathan} completed the work on the project.

Last Friday {Campbell/Clarence} and George left work early after {Campbell/Clarence} completed the work on the project.

28. In the winter {Benjamin/Jonathan} and Morgan liked to play cards with friends so {Benjamin/Jonathan} offered to host a game each weekend.

In the winter {Campbell/Clarence} and Morgan liked to play cards with friends so {Campbell/Clarence} offered to host a game each weekend.

29. A few days ago Austin and {Daniel/Thomas} went to the post office once {Daniel/Thomas} had finished the letters.

A few days ago Austin and {Duncan/Herman} went to the post office once {Duncan/Herman} had finished the letters.

30. Every summer {Daniel/Thomas} and Kelsey had a lovely garden because {Daniel/Thomas} gave good advice about what to grow.

    Every summer {Duncan/Herman} and Kelsey had a lovely garden because {Duncan/Herman} gave good advice about what to grow.

31. Based on the schedule {Joseph/Justin} and Phillip wrote the lyrics to the song before {Joseph/Justin} composed the music.

    Based on the schedule {Weston/Willis} and Phillip wrote the lyrics to the song before {Weston/Willis} composed the music.

32. Each spring Donald and {Joseph/Justin} planted the grass seed before {Joseph/Justin} watered the new lawn.

    Each spring Donald and {Weston/Willis} planted the grass seed before {Weston/Willis} watered the new lawn.

33. Unfortunately Cameron and {Jeffrey/William} had already left for the skip trip when {Jeffrey/William} caught the flu.

    Unfortunately Cameron and {Brenton/Malcolm} had already left for the skip trip when {Brenton/Malcolm} caught the flu.

34. After studying hard {Jeffrey/William} and Brendan got an A in the course so {Jeffrey/William} wanted to celebrate.

    After studying hard {Brenton/Malcolm} and Brendan got an A in the course so {Brenton/Malcolm} wanted to celebrate.

35. In spite of the rain {Charles/Stephen} and Dustin enjoyed the concert at which {Charles/Stephen} met the band.

    In spite of the rain {Dominic/Forrest} and Dustin enjoyed the concert at which {Dominic/Forrest} met the band.

36. On the weekends Russell and {Charles/Stephen} liked to watch the birds unless {Charles/Stephen} needed the binoculars for camping.

    On the weekends Russell and {Dominic/Forrest} liked to watch the birds unless {Dominic/Forrest} needed the binoculars for camping.

37. With much enthusiasm Colin and {Brian/Jason} went to the play when {Brian/Jason} won the tickets in a contest.

    With much enthusiasm Colin and {Jonah/Myles} went to the play when {Jonah/Myles} won the tickets in a contest.

38. After the trip {Brian/Jason} and Logan developed the film as soon as {Brian/Jason} finished the roll.

    After the trip {Jonah/Myles} and Logan developed the film as soon as {Jonah/Myles} finished the roll.

39. If asked Frank and {Kevin/Scott} always sang at parties when {Kevin/Scott} rolled out the piano.

    If asked Frank and {Brock/Cecil} always sang at parties when {Brock/Cecil} rolled out the piano.

40. Until last year Corey and {Kevin/Scott} often bought books online until {Kevin/Scott} thought of borrowing them from the library.

Until last year Corey and {Brock/Cecil} often bought books online until {Brock/Cecil} thought of borrowing them from the library.

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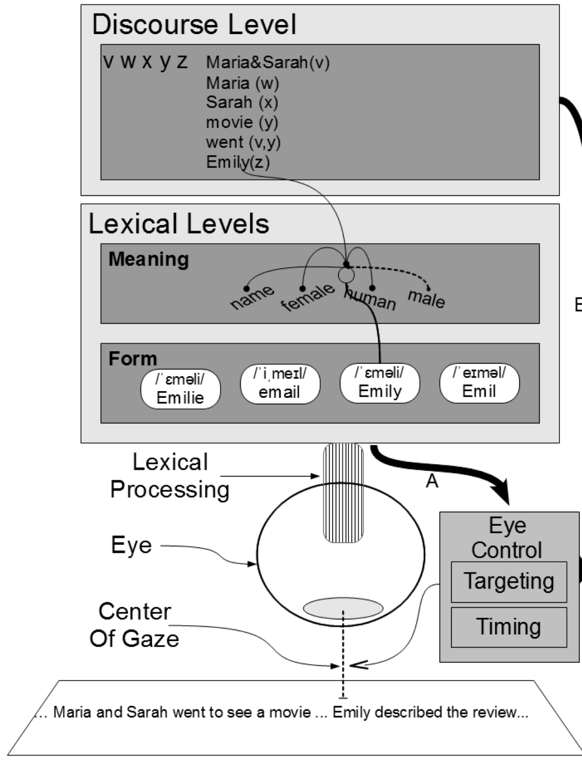

Figure 1.

Model illustrating how language comprehension contributes to eye-movement control during reading. The control of the targeting and timing of saccades is influenced by processes occuring at the lexical level and the discourse level. Word recognition at the lexical level makes a major contribution to the timing of saccades and in some cases their targeting, with ease of word recognition having a strong effect on measures of first-pass reading (as shown by the arrow marked A). While basic word recognition goes on, the effort to understand the meaning of the sentence proceeds by accessing and updating a discourse-level representation in long-term (episodic) working memory of the characters and events depicted by the text. Difficulties at this level of comprehension can affect eye-movement control (as shown by the arrow marked B), an effect that primarily appears in later measures of eye movements such as rereading.

Table 1

Eye-tracking results. Mean reading-time measures (in milliseconds) include: single-fixation duration (SFD), first-fixation duration (FFD), gaze duration (GZD), rereading duration, and total time. Skipping is presented as a proportion.

Region of Interest	Condition	Measure					
		Skipping	SFD	FFD	GZD	Rereading	Total Time
Prime	High-frequency/Repeated	.12	214	211	239	256	484
	High-frequency/New	.08	214	213	251	301	535
	Low-frequency/Repeated	.05	233	226	286	308	584
	Low-frequency/New	.09	237	232	296	340	622
Target	High-frequency/Repeated	.23	193	194	209	148	356
	High-frequency/New	.23	197	198	213	210	397
	Low-frequency/Repeated	.22	194	192	208	153	346
	Low-frequency/New	.12	214	214	244	209	440
Post-Target Region	High-frequency/Repeated				287	167	444
	High-frequency/New				295	207	485
	Low-frequency/Repeated				291	185	463
	Low-frequency/New				295	223	507