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The Effects of Neighborhood Frequency in Reading and Lexical Decision

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To test the effect of the frequency of orthographic "neighbors" on the identification of a printed word, two sets of words were constructed (equated on the number of neighbors, word frequency, and number of letters); in one set, the words had no higher frequency neighbors and in the other set, they had at least one higher frequency neighbor. Identification was slower for the latter set. In Experiment 1, this was indexed by longer response times in a lexical decision task. In Experiment 2, the target words were embedded in sentences, and slower identification was indexed by disruptions in reading: more regressions back to the words with higher frequency neighbors and longer fixations on the text immediately following these words. The latter results indicate that a higher frequency neighbor affects relatively late stages of lexical access, an interpretation consistent with both activation–verification and interactive activation models.

In the last 10 years, there has been a great deal of interest in how the identification of a visual word is affected by its "neighbors," that is, words that are visually similar to it (Andrews, 1989, 1992; Forster & Shen, 1996; Grainger & Jacobs, 1996; Grainger, O'Regan, Jacobs, & Segui, 1989, 1992; Johnson & Pugh, 1994; Paap & Johansen, 1994; Sears, Hino, & Lupker, 1995; Snodgrass & Mintzer, 1993). A major reason for the interest in this topic is that accounting for these effects has become an important issue for models of word recognition. Common to many of the models of word processing developed in the last 25 years is the notion that a visual word activates not only its own memory representation in the lexicon but also memory representations of words that are orthographically "close" to it (e.g., the search model, Forster, 1976; the multiple read-out model, Grainger & Jacobs, 1996; the activation–verification model, Paap, Newsome, McDonald, & Schvaneveldt, 1982; and the interactive activation model, McClelland & Rumelhart, 1981).

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The issue of how neighbors could affect the identification of a word is complex. On the one hand, if the final identification of the actual word involves not only activation of its lexical entry but selection of this entry over those of its neighbors, the presence of these neighbors would have an inhibitory effect on lexical access. On the other hand, in many of these models, the presence of neighbors has a facilitative effect because these neighbors help to "support" the identification of component letters over other, competing, visually similar letters that might have appeared in the same location in the word. Moreover, in some of the models, these inhibitory and facilitative effects would be expected to have different time courses: the facilitative effects plausibly occurring early because they are affecting letter identification and the inhibitory effects occurring late because they are affecting a final selection process in identifying the word. As a result, there is significant interest in whether neighborhood effects are primarily facilitative or inhibitory and in which circumstances facilitative and inhibitory effects occur.

As indicated above, a metaphor driving many of these models of neighborhood effects is that a *candidate set* of lexical entries is selected early in lexical processing. This is a set of lexical entries established by early stages of word identification from which the lexical entry that is ultimately accessed is selected. The candidate set is usually assumed to be the set of lexical entries of orthographic neighbors of the visual word presented. The proper theoretical definition of a neighbor is far from certain. However, largely as a matter of convenience, virtually all of the neighborhood studies cited above have adopted Coltheart, Davelaar, Jonasson, and Besner's (1977) definition of an *orthographic neighbor:* any word that can be created by changing one letter of the stimulus word while preserving the other letter positions (e.g., *horse* and *mouse* are orthographic neighbors of *house*). Hence, most of the studies investigating neighborhood effects have manipulated characteristics of this putative candidate set.

The two primary variables that have been manipulated are

(a) the number of neighbors (*neighborhood size*), which is often referred to as *N*, and (b) whether or not a word has higher frequency neighbors (*neighborhood frequency*). The focus in the current article is on the effects of neighborhood frequency because we feel that it is easier to define empirically and to interpret theoretically. Empirically, varying neighborhood frequency while holding neighborhood size constant is conceptually straightforward: One simply selects two words with equal numbers of neighbors and varies the frequency characteristics of the words in the neighborhood. In contrast, varying neighborhood size while holding the frequency of the neighbors constant is somewhat problematic. That is, when two words have neighborhoods of different sizes, it is far from clear which frequency measure of the neighborhood should be kept constant. Reasonable arguments could be made for the number of higher frequency neighbors, the average frequency of the neighbors, the summed frequency of the neighbors, the maximum frequency in the neighborhood, as well as several other measures.

One simple and common way to vary neighborhood frequency is to select two words matched on neighborhood size, one of which has (at least) one higher frequency neighbor and the other of which has no higher frequency neighbors. (The sets are usually equated on word frequency and number of letters in addition to being equated on neighborhood size.) Many studies examining this manipulation have reported an inhibitory effect of having higher frequency neighbors. This effect makes sense if an important phase of word identification is selection of the actual lexical item from a candidate set, because a higher frequency neighbor should compete more actively for final selection than should lower frequency neighbors. (We delay a more detailed theoretical discussion of this until later.) An inhibitory neighborhood frequency effect has been reported in the lexical decision task (Carreiras, Perea, & Grainger, 1997; Grainger, 1990; Grainger & Jacobs, 1996; Grainger & Segui, 1990; Grainger et al., 1989, 1992; Huntsman & Lima, 1996; however, see Forster & Shen, 1996; Sears et al., 1995) and in speeded identification tasks (Carreiras et al., 1997; Grainger & Jacobs, 1996; Grainger & Segui, 1990) in which participants identify briefly presented words. In addition, Grainger et al. (1989, Experiment 2) also found an inhibitory neighborhood frequency effect in a semantic categorization task that used eye movements. In this latter task, participants first fixated the target word and then fixated a comparison word. Participants had to decide whether the two words were semantically related. The sum of the fixation times on the target word before the eyes moved to the comparison word (the gaze duration) was longer for the words with higher frequency neighbors. In contrast, the effect of neighborhood frequency appears to be slightly facilitative in the naming task, especially for words with many orthographic neighbors (Carreiras et al., 1997; Grainger, 1990; Sears et al., 1995).

There are differences among these studies other than the choice of tasks: Not only are the materials different, but they have been conducted in several different languages. However, the results seem reasonably consistent within a task. One attempt to reconcile these results explained the facilitative effects in the naming task as being due to task-specific processes (Grainger, 1990; Grainger & Jacobs, 1996). However, other analyses might isolate the inhibitory effects as being task-specific. The problem, of course, is that all of these studies involved individuals making responses to isolated words, so that all of the studies contain components not used in normal (silent) reading (e.g., see Balota & Chumbley, 1984; Paap & Johansen, 1994; Snodgrass & Mintzer, 1993).

Our main goal in this article is to shed more light on the effects of a word's neighbors in normal reading by examining the pattern of eye movements when target words varying in neighborhood frequency are embedded in sentences. If neighborhood frequency effects are found (i.e., if the fixation times on words in the target word region and/or the fixation pattern are affected by neighborhood frequency), then one has clear evidence that neighborhood effects are not restricted to laboratory word identification tasks but are actually influencing reading. Moreover, if the text materials are set up so that the words differing on neighborhood frequency are equated in terms of being equally easy to integrate into the sentence context, such effects would indicate that neighborhood frequency is affecting some aspect of word identification. Whether such effects would be a clear demonstration that neighborhood frequency affects lexical access might depend on one's definition of *lexical access*. For some, lexical access means access of the visual or orthographic code, and the reading data would not be particularly diagnostic. To others, lexical access could mean identification of the phonological code, access of semantic codes, or access of all of the above. We remain a bit agnostic on the issue; we use *lexical access* to mean access of whatever codes are necessary in reading to support construction of a syntactic and semantic analysis of a sentence.

Another advantage of eye-movement techniques is that they have the power to shed light on the time course of these effects because the sequence of eye movements offers a sequential record of the processing of the text material. More specifically, it has been found that the frequency of a target word has both fairly immediate effects and more delayed effects on this record. The immediate effects are on the fixation durations on the target word: both the *gaze durations*, the sum of all fixations on the target word before the reader moves to a succeeding word, and the *first-fixation duration* on the target word. The more delayed effects are in "spillover" on succeeding fixations, such as the duration of the first fixation after the reader leaves the target word. These and other data that we discuss in greater detail later have led to a theory of eye-movement control (Reichle, Pollatsek, Fisher, & Rayner, 1998; see also Pollatsek & Rayner, 1990) which posits that early stages of lexical access (whose duration is presumably correlated with word frequency) are responsible for the word frequency effects on first-fixation duration and gaze duration but that full lexical access (or, more precisely, the difference in completion time between the early stages and full lexical access) is responsible for spillover effects. Thus, if our supposition stated earlier was correct, one might conceivably find facilitative effects of neighborhood frequency early in processing (perhaps on first-fixation duration) but inhibitory effects later on (perhaps in spillover or other measures of processing after the reader has initially left the target word).

Our major focus is neighborhood effects in reading text. However, because this is the initial experiment to focus on this area, we also wanted to collect data from one of the more standard paradigms to use as a guide of what to expect in a reading experiment using the same materials and participant population. We chose the lexical decision task because it has been studied most intensively. We expected to find an inhibitory effect of neighborhood frequency in the lexical decision task because most of the studies investigating neighborhood frequency have found a reliable inhibitory effect. However, most of the evidence for this inhibitory effect comes from other languages such as French (Grainger, 1992; Grainger & Jacobs, 1996; Grainger et al., 1989, 1992; Grainger & Segui, 1990), Dutch (Grainger, 1990), and Spanish (Carreiras et al., 1997), although there is one report of an inhibitory neighborhood frequency effect in English (Huntsman & Lima, 1996).[1] However, there have also been a couple of recent failures to obtain the effect in English (Forster & Shen, 1996; Sears et al., 1995).

We will defer a complete discussion of these inconsistencies until later. However, as a result of these inconsistencies, we designed our materials in an attempt to maximize the chances of obtaining a reliable effect. First, we selected a large number of words in each condition (i.e., words with at least one higher frequency neighbor and words with no higher frequency neighbors), and most of our words were relatively low in frequency (because the effects of neighborhood frequency seem to be stronger for lower than for higher frequency words, Grainger & Jacobs, 1996). In addition, we chose our higher frequency neighbors so they differed from the target words by a letter in an interior position of the word (e.g., *spice* is one of our words, and its higher frequency neighbor is *space*). We imposed this restriction because many views of word identification posit that interior letters are processed less well and hence that neighbors that differ from a lexical item by an interior letter are likely to be more interfering than neighbors that differ on either the first or last letter of the word (see Forster, 1976; Grainger & Segui, 1990; Havens & Foote, 1963; Jordan, 1990). Finally, for the lexical decision task, we also stressed to the participants the accuracy of the responses over speed in order to avoid shallow processing of the stimuli (e.g., Grainger & Jacobs, 1996; Paap & Johansen, 1994; Snodgrass & Mintzer, 1993).

Experiment 1

Method

Participants. Twenty-four undergraduate students from the University of Massachusetts at Amherst participated in this experiment in exchange for course credit. All of them had either normal or corrected-to-normal vision and were native speakers of American English.

Design and materials. The 92 target words were either five or six letters in length (66 were five-letter words, and 26 were six-letter words). Forty-six of the target words had higher frequency neighbors, and the other 46 target words had no higher frequency neighbors. All the target words had frequencies of 55 or less in the Kučera and Francis (1967) count, and the number of neighbors (*N* value) for the target words varied from 1 to 7. In all cases, the words with higher frequency neighbors had higher frequency neighbors that differed at a middle letter (the third or the fourth letter for five-letter words, and the third, fourth, or fifth letter for six-letter words) and were substantially higher in frequency than the target word.[2] The 92 words formed 46 pairs in which the two words in each pair were matched on length and were approximately matched on frequency. (Another constraint on the pairs was that the two words had to fit equally felicitously into the same sentence frame used in Experiment 2; thus, matching on frequency for an individual pair was only approximate.) The characteristics of the target words are presented in Table 1, and the target words are presented in Appendix A. The set of 92 orthographically legal nonwords used for the lexical decision task was created by changing one of the middle letters in words of similar length. The words that were used to create the nonwords were drawn from the same pool as the experimental words but were not used as experimental stimuli because it was difficult to find the appropriate matched words for them that were needed for Experiment 2 (see Appendix B). Each participant saw all of the 92 target words and the 92 nonwords.

Table 1
Characteristics of the Target Words in Experiments 1 and 2

Neighborhood frequency	Word frequency (per million)		Neighborhood size (Coltheart *N*)		Number of higher frequency neighbors	
	M	*SD*	*M*	*SD*	*M*	*SD*
Words with higher frequency neighbors	12.5	14.7	3.5	1.8	1.8	1.0
Words with no higher frequency neighbors	11.9	12.7	2.1	1.3	0.0	0.0

The stimuli (in lowercase letters) appeared on the screen as white characters on a dark background. Each character subtended approximately 0.38° of visual angle from a viewing distance of 60 cm, so that five-letter words and six-letter words subtended about 1.90° and 2.28° of visual angle, respectively.

Procedure. Participants were tested individually in a quiet room. Presentation of the stimuli and recording of latencies were controlled by a PC-compatible 286 computer. The timing of responses was accurate to the nearest millisecond. On each trial, a "ready" symbol (a "+") was presented for 500 ms on the center of the screen. After a 200-ms interstimulus interval during which the screen was blank, a lowercase letter string (word or nonword), also centered on the screen, was presented until the participant made a

[1] In addition, in a cross-modal priming study, Marslen-Wilson (1990) found that, for the baseline prime condition (in which the prime had no effect on the participant's response to the visually presented word), low-frequency words with higher frequency neighbors were responded to more slowly than were low-frequency words with no higher frequency neighbors.

[2] In the group of words with higher frequency neighbors, there were words that also had higher frequency neighbors that differed from the words in other than the middle letter positions. For example, *stork* has the higher frequency neighbor *story* in addition to the higher frequency neighbor *stock*.

response. Participants were instructed to press one of two buttons on a response box (the right one for "yes" and the left one for "no") to indicate whether the letter string was an English word or not. Participants were instructed to make their responses as rapidly and as accurately as possible; however, we stressed accuracy in order to avoid shallow processing of the stimuli. The intertrial interval was 1.5 s. Each participant received 24 practice trials prior to the 182 experimental trials. The order of stimulus presentation in the experimental block was randomized, with a different order for each participant. The whole session lasted approximately 11 min.

Results

Incorrect responses (144 observations, or 6.52% of the total) and reaction times greater than 1,500 ms or less than 300 ms (19 observations, or 0.86% of the total) were removed from the response time analyses. In addition, target words on which there were 33% or more errors were discarded. As a result, two words in the condition with no higher frequency neighbors (*villa* and *lasso*) and two words in the condition with higher frequency neighbors (*noose* and *verve*) were eliminated.[3] The error rate for the nonwords was 9.14%.

Our primary focus was on the mean response times, and these were assessed for reliability over both participants (F_1) and items (F_2). In our first analysis, we assessed whether there was a neighborhood frequency effect, ignoring the frequency of the target words. There was an inhibitory effect of 26 ms for having a higher frequency neighbor (632 ms for the words with higher frequency neighbors vs. 606 ms for the words with no higher frequency neighbors), which was highly reliable over participants, $F_1(1, 23) = 12.69$, $MSE = 608$, $p < .002$, but only marginally reliable over items, $F_2(1, 41) = 2.28$, $MSE = 2{,}849$, $p < .07$. For the error data, the neighborhood frequency effect was in the same direction but very small. The error rates were 5.0% for the words with higher frequency neighbors and 4.3% for the words with no higher frequency neighbors (both Fs < 1).

The most likely explanation for the lack of reliability of the effect over stimuli is that it is dependent on the frequency of the target word (i.e., the inhibitory mechanisms underlying the neighborhood frequency effect are likely to be stronger for low-frequency words). Accordingly, we decided to divide each of the two experimental sets into two groups as a function of word frequency: *Low-frequency* words were those with fewer than 10 occurrences per million, and *medium-frequency* words were those with at least 10 occurrences per million. This created a factorial design with two factors: word frequency (low- vs. medium-frequency words) and neighborhood frequency (words with higher frequency neighbors vs. words with no higher frequency neighbors). The characteristics of the words in the experimental conditions are shown in Table 2. (Note that there were somewhat fewer words in the medium-frequency condition. In addition, because individual word pairs were only approximately equated for frequency, the members of a few pairs were on opposite sides of the frequency cutoff. As a result, the matched item design had to be abandoned in the analyses below.)

Not surprisingly, there was a substantial main effect of word frequency, $F_1(1, 23) = 111.36$, $MSE = 1{,}472$, $p < .001$ and $F_2(1, 84) = 33.32$, $MSE = 4{,}627$, $p < .001$. As in our prior analysis, the main effect of neighborhood frequency was significant in the analysis by participants, $F_1(1, 23) = 11.851$, $MSE = 1{,}023$, $p < .003$, but not in the analysis by items, $F_2(1, 84) = 2.33$, $MSE = 4{,}627$, $p = .13$. The interaction between word frequency and neighborhood frequency was significant in the analysis by participants, $F_1(1, 23) = 9.83$, $MSE = 972$, $p < .005$, but not in the analysis by items, $F_2(1, 84) = 2.65$, $MSE = 4{,}627$, $p < .11$. This reflected the fact that there was a 39-ms inhibitory neighborhood frequency effect for the low-frequency words that was reliable over both participants and items, $F_1(1, 23) = 14.08$, $MSE = 1{,}534$, $p < .002$ and $F_2(1, 84) = 5.92$, $MSE = 4{,}627$, $p < .02$, in contrast to a 2-ms effect in the opposite direction for the medium-frequency words (both Fs < 1). Hence, the lack of reliability of the neighborhood effect over all the items appeared to be due to the modulation of the effect by word frequency.

The error data showed a similar pattern (see Table 3). Overall, there were fewer errors for the medium-frequency words than for the low-frequency words, $F_1(1, 23) = 15.90$, $MSE = 20.5$, $p < .001$ and $F_2(1, 84) = 5.97$, $MSE = 48.9$, $p < .02$, and, as with the response times, there was an interaction between word frequency and neighborhood frequency that was reliable over participants, $F_1(1, 23) = 8.34$, $MSE = 10.7$, $p < .009$, but not over items, $F_2(1, 84) = 1.63$, $p > .20$. The pattern of this interaction was similar to that of the response times: There was an inhibitory effect of 2.4%

Table 2
Characteristics of the Target Words for the Word Frequency Analysis in Experiment 1

Experimental condition	Mean word frequency	Mean Coltheart N	Number of words per condition
Low-frequency words with higher frequency neighbors	2.8	3.0	28
Low-frequency words with no higher frequency neighbors	3.6	2.5	27
Medium-frequency words with higher frequency neighbors	26.3	4.2	19
Medium-frequency words with no higher frequency neighbors	24.8	2.5	18

[3] Although these words are not unfamiliar, perhaps the fact that they were loan words seen in isolation, combined with the time pressures of the lexical decision task, caused participants to frequently consider them as nonwords. In fact, participants had no problems with these words in normal reading (Experiment 2). In Experiment 1 (but not in Experiment 2), the target word *flyer* was spelled like its less frequent variant *flier*. For that reason, *flier* was considered as a word with higher frequency neighbors. The analyses reported here include *flier;* however, they were virtually identical when *flier* was removed.

Table 3
Mean Reaction Times (RTs; in Milliseconds) and Percentages of Errors on Words in Experiment 1

Word frequency	Words with higher frequency neighbors		Words with no higher frequency neighbors		Difference	
	RT	%	RT	%	RT	%
Medium	572	1.8	570	3.2	2	−1.4
Low	675	7.4	633	5.0	42	2.4
Difference	103	5.6	63	1.8	40	3.8

for the low-frequency words and a facilitative effect of 1.4% for the medium-frequency words.

In sum, in Experiment 1 there were inhibitory effects of neighborhood frequency that were quite reliable over participants and were reliable for the lower frequency words. One difference between the current experiment and those of Forster and Shen (1996) and Sears et al. (1995), in which reliable inhibitory effects of neighborhood frequency were not observed, is that our higher frequency neighbors always differed from the target word by a middle letter (e.g., *spice,* whose higher frequency neighbor is *space*), which should have increased the inhibitory effect of these neighbors by increasing the confusability with the target. In addition, the percentage of errors in our experiment was smaller than that in the Forster and Shen (1996) experiment, which might reflect "deeper" processing of the stimuli in our experiment (see Snodgrass & Mintzer, 1993), and our words were somewhat lower in frequency than those of Sears et al. (1995). We discuss these points more fully in the General Discussion section.

Experiment 2

Experiment 1 demonstrated that there is a reliable inhibitory effect produced by the presence of a higher frequency neighbor in a lexical decision task for lower frequency words, at least for words whose higher frequency neighbors differ from the target word by an interior letter. We now wanted to determine whether this inhibitory effect would be observed when people were engaged in silent reading as well as in making lexical decision judgments.

Experiment 2 was a straightforward extension of Experiment 1. We constructed sentence frames that contained a matched pair of words (one with at least one higher frequency neighbor and the other without higher frequency neighbors). Somewhat surprisingly, it was not hard to embed pairs of these words in sentence frames so that the two words were equally natural, even though the words were not synonyms. The key question was whether the sentence containing the word with the higher frequency neighbor was harder to read than the sentence containing the word with no higher frequency neighbors. Of particular interest in the analysis were the duration of fixations on the target word and the region following it and the pattern of regressions from the succeeding region back to the target word.

Method

Participants. Twenty-four students from the University of Massachusetts took part in the experiment in exchange for course credit or money. None had participated in the previous experiment. All were native speakers of American English and either had normal vision or normal vision when corrected by soft contact lenses.

Materials. The stimuli were a set of 46 pairs of sentences (see Appendix A) that used the 92 target words of Experiment 1. The two members of each pair were identical except for the target word (one target word having higher frequency neighbors and the other having no higher frequency neighbors). To make sure that any differences that we observed in the experiment were due to access of the target words rather than to their relative appropriateness in the sentence, we had 13 participants judge each of the 46 pairs of sentences. They were given each pair of sentences and were asked to judge which of the two sentences was more natural (if either). The naturalness judgments for the sentences with the target words with higher frequency neighbors and for the sentences with the target words with no higher frequency neighbors were virtually identical: 31% of the time the sentence containing the target word with higher frequency neighbors was judged as the more natural; 31% of the time the sentence containing the target word with no higher frequency neighbors was judged as the more natural; and 38% of the time the two sentences were judged as equally natural. Each stimulus sentence was no more than 80 characters and spaces in length and occupied one line on the CRT display screen.

Design. Two lists were created, each containing 46 experimental sentences. Each list contained 23 sentences with target words that had higher frequency neighbors and 23 sentences with target words that had no higher frequency neighbors. The presence of the target words was counterbalanced across the two lists so that if a word with higher frequency neighbors (e.g., *spice*) appeared in one list, its corresponding target word with no higher frequency neighbors (*sauce*) appeared in the other list. The two target words in the same sentence frame had the same number of letters and were of approximately equal frequency. Before reading any experimental sentences, each participant completed eight trials with practice sentences to become familiar with the procedure.

Apparatus. Eye movements were recorded by a Fourward Technologies (San Marcos, TX) Dual Purkinje Eyetracker, which has a resolution of less than 10′ of arc and an output that is linear over the angle subtended by a line of text. The eyetracker was interfaced with an ACI 486 computer. The position of the participant's eye was sampled every millisecond, and each 4 ms of eyetracker output was compared with the output of the previous 4 ms to determine whether the participant's eyes were fixed or moving. The computer stored the duration and location of each fixation for later analysis. The computer was also interfaced with a View Sonic 17G display on which the sentences were presented. The display was 61 cm from the participant's eye, and four characters equalled 1° of visual angle. Viewing was binocular, but eye movements were recorded from the participant's right eye. A bitebar was used to eliminate head movements in the experiment.

Procedure. When a participant arrived for the experiment, a bitebar was prepared and the eyetracking system was calibrated. The calibration period usually lasted less then 5 min. After the calibration was completed, participants were told that they would be given sentences to read. They were told that the purpose of the experiment was to determine what people look at as they read. Participants were told to read each sentence for normal comprehension. To ensure comprehension, after 25% of the sentences we asked them to answer comprehension questions about the sentence they had just read. Participants had little difficulty answering the questions correctly.

Data analysis. Several dependent variables were of major interest. The first group consisted of measures of "first pass" processing on the fixated word: (a) the *first-fixation duration* (the duration of the first fixation on the target word), (b) the *gaze duration* (the sum of the fixation durations on the target word before the reader left the target word, and (c) the probability of fixating the target word. (For all of these analyses, the *target region* was defined as the target word plus the space that preceded it.) For both of the above fixation duration measures, trials are counted only when the reader initially fixates the word with a forward saccade; moreover, the measures are conditional—the averages are taken only over trials on which the word was not initially skipped. The second group of measures assessed processing after the reader left the target word on his or her first pass through the text. These included *spillover effects,* such as the duration of the first fixation after leaving the target word, the probability of making a regression back to the target word, the *total time* spent on the target word (the sum of all fixation durations on the target word including regressive fixations), and the total time spent on the target word plus the immediate posttarget region. The *immediate posttarget region* was defined as the two words subsequent to the target word; a region of two words was chosen because the word immediately following the target word was often a function word and hence was often skipped (see Appendix A).

Results

A few sentences were excluded from the analysis because of problems with monitoring the eye movements. First, somewhat fewer than 3% of the trials were eliminated because there was a track loss while participants were reading the sentence. Second, there were a few trials (about 0.1%) in which the participants were not fixating where they were supposed to when the sentence appeared. As in Experiment 1, the reliability of effects was assessed across both participants and items. (Because word length and frequency were equated across pairs of items, neighborhood frequency was treated as a within-item variable in the item analyses, thereby increasing the power of the analysis.) The data are presented in Table 4.

The first thing to note is that there was no clear effect of neighborhood frequency on any of the first pass variables. Overall, there were only a 4-ms effect on first-fixation duration, a 2-ms effect on gaze duration, and a 0.5% effect on the probability of skipping the target word (all *p*s $> .20$). Thus, any effects of neighborhood frequency that occurred prior to or while the reader fixated the target word were small and not sufficiently reliable over the set of participants that we ran.

In contrast, there were quite reliable neighborhood effects that occurred after the reader left the target word. The most reliable was the effect of neighborhood frequency on the probability of a regression back to the target word, $F_1(1, 23) = 29.85$, $MSE = 13.7$, $p < .001$ and $F_2(1, 45) = 13.30$, $MSE = 75.52$, $p < .001$. Overall, readers regressed back to the target word about twice as often when it had higher frequency neighbors. In addition, there was a reliable 12-ms effect of neighborhood frequency on the duration of the first fixation subsequent to the target word (a spillover effect), $F_1(1, 23) = 4.41$, $MSE = 400$, $p < .05$ and $F_2(1, 45) = 6.42$, $MSE = 458$, $p < .02$. The impact of regressions back to the target word can also be assessed by examining the total time readers spent fixating the target word. As can be seen in Table 4, readers spent an average of 23 ms longer on the target words that had higher frequency neighbors, $F_1(1, 23) = 4.78$, $MSE = 1{,}348$, $p < .04$ and $F_2(1, 45) = 5.59$, $MSE = 3{,}368$, $p < .03$. Perhaps the best global measure of the cost of having at least one higher frequency neighbor is the total time spent on the target word and the posttarget region consisting of the following two words. As can be seen in Table 4, this cost is 39 ms, which is an increase in processing time of about 5%, $F_1(1, 23) = 7.66$, $p < .02$ and $F_2(1, 45) = 8.23$, $p < .007$.

Table 4
Eye-Movement Measures for the Target Words in Experiment 2 As a Function of Neighborhood Frequency

Measure of reading	Words with higher frequency neighbors	Words with no higher frequency neighbors	Difference
First-fixation duration on target word (in milliseconds)	266	262	4
Gaze duration on target word (in milliseconds)	292	290	2
Probability of skipping target word (%)	13.6	14.1	0.5
Duration of first fixation after target word (in milliseconds)	261	249	12
Percentage of regressions back to target word	13.5	6.9	6.6
Total time on target word (in milliseconds)	340	317	23
Total time on target word plus posttarget region (in milliseconds)	747	708	39

As in Experiment 1, we also conducted analyses in which we divided the target words into two groups as a function of word frequency (fewer than 10 occurrences per million vs. at least 10 occurrences per million) in order to assess the influence of word frequency on the neighborhood frequency effects (see Table 5). The pattern of results was similar to that in Experiment 1 in that the effects of neighborhood frequency appeared to be stronger for the low-frequency words; however, unlike the case in Experiment 1, the inhibitory effect did not disappear for the medium-frequency words. (Although the inhibitory effect appeared to be weaker for the medium-frequency words, none of the analyses of variance showed a reliable interaction between neighborhood frequency and word frequency, with all *p* values greater than .10.) Unlike the situation in Experiment 1, the effects of the frequency of the target word were not particularly reliable, perhaps because the sentence frames were different for the low- and medium-frequency words. The most reliable target word frequency effect was the spillover effect, $F_1(1, 23) = 4.61$, $MSE = 669$, $p < .05$ and $F_2(1, 88) = 4.10$, $MSE = 539$, $p < .05$; even the 62-ms

Table 5
Eye-Movement Measures for the Target Words in Experiment 2 As a Function of Word Frequency and Neighborhood Frequency

	Low-frequency words			Medium-frequency words		
Measure of reading	Words with higher frequency neighbors	Words with no higher frequency neighbors	Difference	Words with higher frequency neighbors	Words with no higher frequency neighbors	Difference
First-fixation duration on target word (in milliseconds)	269	264	5	263	257	6
Gaze duration on target word (in milliseconds)	294	293	1	288	280	8
Probability of skipping target word (%)	13.5	12.3	−1.2	14.0	17.2	3.2
Duration of first fixation after target word (in milliseconds)	268	253	15	253	244	9
Percentage of regressions back to target word	16.1	6.6	9.5	9.8	7.2	2.6
Total time on target word (in milliseconds)	351	321	30	326	304	22
Total time on target word plus posttarget region	785	715	70	695	682	13

frequency effect on total time was significant only over participants, $F_1(1, 23) = 5.35$, $MSE = 1{,}973$, $p < .05$ and $F_2(1, 88) = 1.68$, $MSE = 4{,}446$, $p > .10$.

We undertook a second post hoc analysis to examine whether there were any meaningful individual differences among participants in the pattern of results, especially in the time course of the neighborhood frequency effects. Accordingly, we divided the 24 participants into two groups of 12 participants each: Group A, those who regressed back to the target word at least 8% of the time, and Group B, those who regressed back to the target word less than 8% of the time. Both groups showed reliable inhibitory effects of neighborhood frequency on the posttarget measures. Both groups regressed back to the target word more frequently for words with higher frequency neighbors than for words with no higher frequency neighbors: 20.5% vs. 12.1%, respectively, for Group A $F(1, 11) = 36.97$, $p < .001$, and 4.4% vs. 1.2%, respectively, for Group B, $F(1, 11) = 6.45$, $p < .03$. Group B also showed a significant inhibitory effect on the first-fixation duration in the posttarget region, $F(1, 11) = 5.13$, $p < .05$. However, there was a different pattern between the two groups for fixations on the target word. For Group A (the group with fewer regressions), there was an inhibitory neighborhood frequency effect in the gaze durations (288 ms for words with higher frequency neighbors vs. 273 ms for words with no higher frequency neighbors), $F(1, 11) = 5.79$, $p < .035$. In contrast, for the group with more regressions, there was actually a facilitative effect of neighborhood frequency (295 ms for words with higher frequency neighbors vs. 307 ms for words with no higher frequency neighbors), although the latter effect was not at all reliable ($F < 1$). This analysis suggests that, for some readers, inhibitory effects of neighborhood frequency may not be delayed until after the target word has been left. However, any conclusions must be tempered by the fact that the division of participants into groups was made on the basis of data taken from the reading task rather than on the basis of an independent measure of reading ability.

General Discussion

The present experiments provide evidence that competing lexical units play a role in word identification, not only in a word–nonword discrimination task (Experiment 1) but also in normal silent reading (Experiment 2). Higher frequency orthographic neighbors appear to inhibit the identification of words, at least in situations in which the target words are relatively low in frequency and when the mismatching letter is in the middle of the word. As indicated earlier, such an inhibitory effect is predicted by many models of visual word recognition, either by a frequency-ordered lexical search (the activation–verification model, Paap et al., 1982; the search model, Forster, 1976) or by competition among lexical units (the interactive activation model, McClelland & Rumelhart, 1981; the multiple read-out model, Grainger & Jacobs, 1996). Our reading data, furthermore, indicate that this inhibitory effect tends to occur relatively late in lexical access, at least for a sizable portion of the participants in the current experiment. Before attempting to establish more detailed links with models of word recognition, however, we need to clarify what we think can be inferred from the pattern of reading data.

Neighborhood Frequency Effects in Reading

As we briefly indicated earlier, lexical effects in reading (most notably word frequency effects) have been shown in many experiments to occur both on fixation durations on the target word and as spillover effects. (Most experiments have confined an examination of spillover effects to the succeeding fixation or two.) In contrast, there is no evidence to date that there are any effects on the durations of fixations prior to the first fixation on a target word that are due to the lexical nature of that target word. This might provoke the tempting conclusion that the lexical processing of a word occurs only when it is fixated and on the following fixation or two. However, the story is more complex than that because a fixation duration may reflect processing that has occurred on a prior fixation. Specifically, we know that processing of a word often starts before it is fixated. For example, frequent or predictable words are skipped more often than less frequent or less predictable words (see Rayner & Pollatsek, 1989, for a review).

Another important piece of data indicating that lexical processing of a word begins before it is fixated comes from eye-movement-contingent display change experiments in which the availability of letter information about a target word before it is fixated (*preview information*) is manipulated. For example, in one type of baseline condition (normal reading), there is no display change and a target word such as *space* is present throughout the time the participant is reading the sentence, whereas in one type of display change condition, a completely uninformative letter string of the same length, such as *cgrns*, appears in the target location until it is fixated and then the word *space* appears. The data from several experiments indicate that both first-fixation duration and gaze duration on the target word are shortened in normal reading compared with when the preview information is unavailable (see Pollatsek & Rayner, 1990, and Rayner & Pollatsek, 1989, for reviews of these experiments). We term this shortening of fixations *preview benefit*. Thus, all we can safely say is that lexical variables begin to affect fixation durations only when the word is fixated (though they might affect the location of fixations even before that).

Recently, we (Reichle et al., 1998) proposed a model of eye movements in reading that was briefly mentioned earlier. This model attempts to account for various major features of the eye-movement record in reading, including frequency effects on fixation durations, word skipping, and preview benefit. Space considerations preclude a full exposition of the model, but elaboration of a few aspects will help focus interpretation of the reading data. Most significantly, the model posits two stages of lexical access: a prior *familiarity check stage* and then a stage of full lexical access. In the model, (a) the familiarity check stage is the signal for an eye movement to be programmed to the next word, and (b) full lexical access is the signal for covert attention to shift to the next word. For convenience, we called the processing that occurs after the initial stage up to full lexical access the *lexical completion stage*. (We do not discuss word skipping here, although the model gives a good account of it as well.) As indicated in the introduction, both the duration of the initial stage and the duration of the lexical completion stage were assumed to be affected by frequency (specifically, assumed to be linear functions of log frequency); the duration of the familiarity check stage is the primary influence on first-fixation durations and gaze durations, and the duration of the lexical completion stage is the primary determinant of spillover effects. Positing two stages, one driving eye movements and one driving covert attention, seemed necessary to account both for spillover effects and for a finding of Henderson and Ferreira (1990; see also Kennison & Clifton, 1995) that preview benefit was modulated by the frequency of the prior word; this is another delayed effect of frequency.

More generally, this was a minimalist attempt to model the reading process so as to enable a more coherent examination of reading data. The division of lexical access into two discrete processing stages was a modeling convenience; however, we remained agnostic about whether there really were two discrete stages that could be conveniently mapped into components of word-processing models or whether the familiarity check stage was merely a partially completed state of lexical access that could be somehow read by a decision stage (e.g., an assessment that excitation in the lexicon has crossed a threshold). We viewed the model as a guide to experiments such as the present one that would explore the properties of these two stages and would help determine whether any coherent picture emerged. However, it is worth restating that whatever the ultimate theoretical interpretation, the eye-movement record allows one to interpret certain effects as occurring "earlier" and other effects as occurring "later."

With this in mind, what can be inferred about the neighborhood effects in our reading data? First, we interpret all the neighborhood effects we observed in reading as being "lexical" in the sense that they relate to identifying the meaning of the target word. Some of these lexical effects may occur as lexical processing is interfacing with higher order processing. However, assuming that we have equated the sentence frames for ease of integration of the target words, any differences in such integration processes must stem from differences in ease of lexical access. Second, the lack of any neighborhood frequency effect on first-fixation durations and gaze durations on the target word that was consistent over participants indicates that neighborhood frequency was not having any consistent effect on the early stages of lexical access, because we know that at least some lexical processing (captured by our familiarity check stage) affects these measures. In contrast, because we observed clear spillover and delayed effects of neighborhood frequency, it appears that these inhibitory effects consistently occur relatively late in lexical processing.

As we mentioned earlier, Grainger et al. (1989) also found an inhibitory neighborhood frequency effect using fixation duration measures as dependent variables. Somewhat at variance with our data was their finding of a significant lengthening of the gaze duration on the target word. However, the participants in their experiment were performing a semantic categorization task, and it is likely that their fixation strategies were different from those in normal reading. Especially because the task was new to them, it seems reasonable to assume that participants in the Grainger et al. experiment may not have moved their eyes until lexical access was complete. In fact, the gaze durations Grainger et al. reported (405 ms for words with no higher frequency neighbors and 457 ms for words with higher frequency neighbors) were substantially longer than those typically observed in normal reading. However, the size of their neighborhood frequency effect (52 ms) is not very different from the difference we observed in the total time on the target word and the subsequent region (39 ms). As a result, it is plausible that both effects are estimates of neighborhood frequency differences in accessing the meaning of a word (for different participant populations and different materials).

Finally, our data on individual differences (admittedly suggestive) have an interesting interpretation in terms of the Reichle et al. (1998) model. Remember that there appeared to be two groups of readers defined by the total number of regressions back to the target word. Both groups had significantly more regressions back to the words with higher frequency neighbors than to the control words. However, the group with a large number of total regressions back to the target word (Group A) had somewhat shorter gaze durations on the target words with higher frequency neighbors, whereas the group with many fewer total regressions back to the target word (Group B) had longer gaze durations on the words with higher frequency neighbors (and longer spillover durations as well). The difference in pattern between the two groups makes sense if one assumes that (total) lexical access time is about the same for both groups of readers but that Group A has a shorter familiarity check stage and a longer lexical completion stage. Moreover, one has to assume that the differing durations of the familiarity check stage for the two groups are largely unrelated to processes related to the neighborhood effects. One simple possibility for how the familiarity check stage might vary in this fashion, hinted at earlier, is that the signal to move the eyes means that total excitation in the lexicon has crossed some threshold but that some readers (i.e., the Group A readers) have lower thresholds than other readers. (For ease of exposition, we refer to the Group A readers as the *more impulsive* readers because they are programming their eye movements using less evidence for lexical access.)

Let us now see how the pattern of data makes sense given this set of assumptions. First, consider the pattern of gaze durations, in which there was a suggestion of a facilitative effect of neighborhood frequency for the more impulsive readers (Group A) and a significant inhibitory effect for the less impulsive readers (Group B). If, as suggested in the introduction, there is a facilitative effect of having higher frequency neighbors early in lexical access, then perhaps this is revealed in the gaze duration for at least some of the more impulsive readers, because the signal to move the eyes off of the target word occurs relatively early in the lexical access process for these readers. However, if the inhibitory processes set in relatively soon after this facilitative effect occurs, then they might quickly offset the facilitative effects, and thus we would mainly observe inhibitory effects on gaze duration for the less impulsive readers.

Second, consider the pattern of data after readers leave the fixated word. The Reichle et al. (1998) model predicts that there will be some regressions back to a word that are due to lexical processing. Other regressions that are due to syntactic processing effects, such as "garden path" effects (e.g., Frazier & Rayner, 1982) and discourse processing effects (e.g., Ehrlich & Rayner, 1983), are beyond the scope of the model. According to the model, a necessary condition for the occurrence of these regressions is that the reader still be attending to word N when his or her eyes have actually moved to word $N + 1$; this state is reached when an eye movement is programmed early in a fixation (when the familiarity check stage is short) and executed when the reader is still attending to word N but has actually programmed the eye movement to word $N + 1$ (i.e., when the lexical completion stage is long). As a result, more of these regressions would be predicted for the more impulsive readers, who have a longer lexical completion stage. It is also worth noting that the Reichle et al. model predicted regressions that were due to this mechanism on about 5% of the fixations, so the size of the effect observed in the current experiment could likely be predicted by a quantitative simulation.

In summary, the overall reading data indicated that the effects of having a higher frequency neighbor occurred late in lexical processing and were inhibitory. However, the division of our data into two groups of readers suggests a somewhat more complex story. That is, there may be one class of readers who trigger eye movements early in lexical processing and for whom all the inhibitory effects occur after this trigger (reflected in spillover effects and many more regressions back to the target word). For these readers, there was also a suggestion of facilitation (on gaze durations) that was due to having a high-frequency neighbor early in processing. For the other class of readers, who trigger eye movements relatively later in lexical processing, only inhibitory effects were observed, but these appeared earlier in the eye-movement record (i.e., on gaze durations as well as spillover measures). That is, all the data are consistent with a facilitative effect of neighborhood frequency occurring early in lexical access followed by a later, and stronger, inhibitory effect. The pattern of individual differences is accounted for by positing that some readers tap into ongoing lexical processing to make an eye movement at an earlier stage than do other readers.

Neighborhood Effects and Models of Visual Word Recognition

In the family of serial search models, as indicated earlier, lexical access is considered to have two stages: (a) an activation of neighborhood "candidates" and (b) selection of the lexical item from among the candidates. The selection process is posited to be a search through the subset of candidates in descending order of word frequency (e.g., Forster, 1976; Paap et al., 1982). As a result, the key factor in recognizing a given word is predicted to be the number of higher frequency neighbors rather than the frequency of the word per se (see Paap & Johansen, 1994). Nonetheless, Paap and Johansen's data are somewhat equivocal. When they used target word frequency and the number of higher frequency neighbors as predictors, no significant effect of word frequency was found, whereas the inhibitory effect of the number of higher frequency neighbors was significant. However, in another analysis in which log of target word frequency was used instead of raw word frequency, the effect of the number of higher frequency neighbors was negligible, and only the effect of log of word frequency was significant. In the present experiments, significant effects of word frequency were obtained even when neighborhood frequency was controlled for: The target word frequency effects were 80 ms in the lexical decision task and 62 ms in the reading task on the total time spent on the target word plus the posttarget region. (The latter effect was not reliable over materials; however, as we indicated earlier, this is probably because the sentence frames were not controlled across frequency classes.) These frequency effects pose a problem for this version of the activation–verification model.

In contrast, parallel models such as the interactive activation model (McClelland & Rumelhart, 1981) and the multiple read-out model (Grainger & Jacobs, 1996) assume that the units corresponding to the more frequent words have higher resting levels than do the units corresponding to less frequent words. Thus, these models predict word frequency effects even when neighborhood effects are controlled for. In addition, in both these parallel models, there is mutual inhibition among the candidates at the lexical level, and a lexical unit is recognized when its level of activation rises significantly above the activation level of other candidates. Words with higher frequency neighbors will take longer to recognize than words with no higher frequency neighbors because higher frequency words are activated before lower frequency words and send inhibition to their lower frequency neighbors, even at the first stages of word processing. In fact, simulations run with the interactive activation model show that the model captured the inhibitory effect of neighborhood frequency quite well: An average of 20.4 processing cycles were needed for words with higher frequency neighbors, and an average of 19.2 processing cycles were needed for words with no higher frequency neighbors (the difference for low-frequency words, 1.3 processing cycles, was slightly larger than that for medium-frequency words, 1.1 processing cycles).[4] The multiple read-out model (Grainger & Jacobs, 1996), which is an extension of the interactive activation model, also posits that there are processes other than full lexical identification that are used in the lexical decision judgment. Specifically, in circumstances where processing is shallow, lexical decisions can be based on a general state of excitation in the lexicon: the sum of the activation levels of all word units. (Shallow processing is posited to occur either when the nonwords are not very wordlike or when speed is emphasized over accuracy.)

We should note that the Seidenberg and McClelland (1989) model makes the opposite prediction in the lexical decision task—an advantage for words with higher frequency neighbors—because the mechanisms responsible for making the lexical decision depend on the familiarity of the letter string rather than on the identification of a lexical unit (for simulations of the effect, see Sears et al., 1995). However, because this model is not strictly applicable to reading, we do not consider it further.

As indicated earlier, however, there is a discrepancy in the literature about the reliability of the neighborhood frequency effect in the lexical decision task. There are several differences among the studies (including the language used), but two salient differences appear to be (a) where participants are on the speed–accuracy trade-off curve in the lexical decision judgment and (b) the frequency of the target words in the language. For the most part, experiments in which the responses are rapid or have relatively high error rates often show no neighborhood frequency effect (Forster & Shen, 1996; Sears et al., 1995), whereas experiments in which the responses are slower and more accurate (including Experiment 1 of the present study) show an inhibitory effect (e.g., Carreiras et al., 1997; Grainger & Jacobs, 1996; Grainger et al., 1989; Huntsman & Lima, 1996). This has led to controversies about which results reflect lexical access and which reflect artifacts of the task.[5]

On the one hand, the argument has been made that when the error rates are high, participants are mainly relying on early stages of lexical access to make lexical decisions, and the effects on these early stages may not tap the inhibitory processes. On the other hand, the argument has been made that when error rates are low, participants are engaged in various double-checking processes, not used in normal lexical access, that produce the inhibitory effects. Experiment 2 indicates that these inhibitory effects are not an artifact of the lexical decision task but instead occur relatively late in the process of lexical access. It is possible, however, that they reflect verification processes that are slow enough so that they affect lexical decision experiments in English only when a word is relatively low in frequency.[6]

In addition, an interesting question is whether the inhibitory effects of higher frequency neighbors are cumulative

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[4] As in previous work by Grainger (1990; Grainger & Jacobs, 1996; Jacobs & Grainger, 1992), the threshold for word node activation levels was set to 0.70 in order to obtain a measure of identification latencies. The parameters used were the ones given by default by McClelland and Rumelhart (1988) except that the letter–word excitation parameter was set to 0.06 for the five-letter words and 0.055 for the six-letter words (see Grainger & Jacobs, 1996, for a similar adjustment).

[5] For instance, in Experiment 3 of the Forster and Shen (1996) study, which used words from a range of frequencies similar to our low-frequency words, error rates of over 10% were reported despite the fact that Forster and Shen's nonwords were not particularly wordlike (i.e., did not have any word neighbors).

[6] Nonetheless, Huntsman and Lima (1996) found a robust neighborhood frequency effect even with a mean word frequency of over 20 per million. However, their mean latencies were relatively slow (over 700 ms), which again may be interpreted in terms of verification processes.

(i.e., whether several higher frequency neighbors cause more inhibition than one). Both the activation–verification model (Paap et al., 1982) and the interactive activation model (Grainger, 1990; McClelland & Rumelhart, 1981) predict a cumulative effect of number of higher frequency neighbors on word identification. The prediction is clearer in the activation–verification model: Words with many higher frequency candidates should be identified more slowly than words with only one higher frequency candidate, because the actual lexical item will be lower on the list the more higher frequency neighbors it has. In the interactive activation model, the effect is cumulative because there is more inhibition from several higher frequency neighbors than from one. The predictions of the latter model are a little less straightforward, however, because the higher frequency neighbors are inhibiting each other. However, the Grainger and Jacobs (1996) model predicts that there will be little or no cumulative effect of neighborhood frequency in the lexical decision task because of the use of task-specific processes. In fact, Grainger et al. (1989; Grainger, 1990; Grainger & Jacobs, 1996) observed that the inhibitory effect on lexical decisions was no bigger when there were several higher frequency neighbors than when there was only one higher frequency neighbor.

We carried out regression analyses on the data while partialing out the effects of word frequency, neighborhood size, number of letters, and number of syllables.[7] For the lexical decision latencies, the number of higher frequency neighbors was only a slightly better predictor ($r = .28$ vs. $r = .26$) than was the dichotomous variable of neighborhood frequency (i.e., words with higher frequency neighbors vs. words with no higher frequency neighbors). However, in the eye-movement data, the number of higher frequency neighbors appeared to be a substantially better predictor than was neighborhood frequency ($r = .31$ vs. $r = .17$ for the spillover effects; $r = .31$ vs. $r = .24$ for the regressions toward the target word; and $r = .28$ vs. $r = .18$ for the total time on the target word). Although more experimental evidence is needed, our data suggest that the effects of neighborhood frequency can be cumulative, at least in tasks in which the identification of the target word is required (see also Grainger & Jacobs, 1996).

Summary

Our experiments certainly do not answer all of the questions about how lexical neighbors influence identification of printed words. However, they clearly indicate that one plausible influence, an inhibitory effect that is due to having a higher frequency neighbor, is real in that it is observed not only in a lexical decision task but also in silent reading. Moreover, the inhibitory effect observed in reading was reasonably consistent in size both with the effect in the lexical decision data and with an effect observed with eye movements in a semantic categorization task (Grainger et al., 1989). In addition, our reading data indicate that the inhibitory effect of having a higher frequency neighbor occurs largely after readers have left the target word, which indicates that this inhibitory effect occurs relatively late in lexical processing. Further study is needed to determine the impact of other neighborhood effects on reading.

[7] The use of log of word frequency instead of word frequency did not appreciably change the correlations with the lexical decision latencies or eye-movement measures, possibly because of the limited range of frequency of the selected words.

References

Andrews, S. (1989). Frequency and neighborhood effects on lexical access: Activation or search? *Journal of Experimental Psychology: Learning, Memory, and Cognition, 15,* 802–814.

Andrews, S. (1992). Frequency and neighborhood effects on lexical access: Lexical similarity or orthographic redundancy? *Journal of Experimental Psychology: Learning, Memory, and Cognition, 18,* 234–254.

Balota, D. A., & Chumbley, J. I. (1984). Are lexical decisions a good measure of lexical access? The role of word frequency in the neglected decision stage. *Journal of Experimental Psychology: Human Perception and Performance, 10,* 340–357.

Carreiras, M., Perea, M., & Grainger, J. (1997). Effects of orthographic neighborhood in visual word recognition: Cross-task comparisons. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 23,* 857–871.

Coltheart, M., Davelaar, E., Jonasson, J. F., & Besner, D. (1977). Access to the internal lexicon. In S. Dornic (Ed.), *Attention and performance VI* (pp. 535–555). Hillsdale, NJ: Erlbaum.

Ehrlich, K., & Rayner, K. (1983). Pronoun assignment and semantic integration during reading: Eye movements and immediacy of processing. *Journal of Verbal Learning and Verbal Behavior, 22,* 75–87.

Forster, K. I. (1976). Accessing the mental lexicon. In R. J. Wales & E. W. Walker (Eds.), *New approaches to language mechanisms* (pp. 257–287). Amsterdam: North-Holland.

Forster, K. I., & Shen, D. (1996). No enemies in the neighborhood: Absence of inhibitory neighborhood effects in lexical decision and semantic categorization. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 22,* 696–713.

Frazier, L., & Rayner, K. (1982). Making and correcting errors during sentence comprehension: Eye movements in the analysis of structurally ambiguous sentences. *Cognitive Psychology, 14,* 178–210.

Grainger, J. (1990). Word frequency and neighborhood frequency effects in lexical decision and naming. *Journal of Memory and Language, 29,* 228–244.

Grainger, J. (1992). Orthographic neighborhoods and visual word recognition. In R. Frost & L. Katz (Eds.), *Orthography, morphology, and meaning* (pp. 131–146). Amsterdam: Elsevier.

Grainger, J., & Jacobs, A. M. (1996). Orthographic processing in visual word recognition: A multiple read-out model. *Psychological Review, 103,* 518–565.

Grainger, J., O'Regan, J. K., Jacobs, A. M., & Segui, J. (1989). On the role of competing word units in visual word recognition: The neighborhood frequency effect. *Perception & Psychophysics, 45,* 189–195.

Grainger, J., O'Regan, J. K., Jacobs, A. M., & Segui, J. (1992). Neighborhood frequency effects and letter visibility in visual word recognition. *Perception & Psychophysics, 51,* 49–56.

Grainger, J., & Segui, J. (1990). Neighborhood frequency effects in visual word recognition: A comparison of lexical decision and masked identification latencies. *Perception & Psychophysics, 47,* 191–198.

Havens, L. L., & Foote, W. E. (1963). The effect of competition on visual duration threshold and its independence of stimulus frequency. *Journal of Experimental Psychology, 65,* 6–11.

Henderson, J. M., & Ferreira, F. (1990). Effects of foveal processing difficulty on the perceptual span in reading: Implications for attention and eye movement control. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 16,* 417–429.

Huntsman, L. A., & Lima, S. D. (1996). Orthographic neighborhood structure and lexical access. *Journal of Psycholinguistic Research, 25,* 417–429.

Jacobs, A. M., & Grainger, J. (1992). Testing a semistochastic variant of the interactive activation model in different word recognition experiments. *Journal of Experimental Psychology: Human Perception and Performance, 18,* 1174–1188.

Johnson, N. F., & Pugh, K. R. (1994). A cohort model of visual word recognition. *Cognitive Psychology, 26,* 240–346.

Jordan, T. R. (1990). Presenting words without interior letters: Superiority over single letters and influence of postmask boundaries. *Journal of Experimental Psychology: Human Perception and Performance, 16,* 893–909.

Kennison, S. M., & Clifton, C. (1995). Determinants of parafoveal preview benefit in high and low working memory capacity readers: Implications for eye movement control. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 21,* 68–81.

Kučera, H., & Francis, W. N. (1967). *Computational analysis of present-day American English.* Providence, RI: Brown University Press.

Marslen-Wilson, W. D. (1990). Activation, competition, and frequency in lexical access. In G. T. M. Altmann (Ed.), *Cognitive models of speech processing: Psycholinguistic and computational perspectives* (pp. 148–172). Cambridge, MA: MIT Press.

McClelland, J. L., & Rumelhart, D. E. (1981). An interactive activation model of context effects in letter perception: Part 1. An account of basic findings. *Psychological Review, 88,* 375–407.

McClelland, J. L., & Rumelhart, D. E. (1988). *Explorations in parallel distribution processing: A handbook of models, programs, and exercises.* Cambridge, MA: MIT Press.

Paap, K. R., & Johansen, L. S. (1994). The case of the vanishing frequency effect: A retest of the verification model. *Journal of Experimental Psychology: Human Perception and Performance, 20,* 1129–1157.

Paap, K. R., Newsome, S. L., McDonald, J. E., & Schvaneveldt, R. W. (1982). An activation-verification model for letter and word recognition: The word superiority effect. *Psychological Review, 89,* 573–594.

Pollatsek, A., & Rayner, K. (1990). Eye movements and lexical access in reading. In D. A. Balota, G. B. Flores d'Arcais, & K. Rayner (Eds.), *Comprehension processes in reading* (pp. 143–163). Hillsdale, NJ: Erlbaum.

Rayner, K., & Pollatsek, A. (1989). *The psychology of reading.* Englewood Cliffs, NJ: Prentice-Hall.

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.

Sears, C. R., Hino, Y., & Lupker, S. J. (1995). Neighborhood frequency and neighborhood size effects in visual word recognition. *Journal of Experimental Psychology: Human Perception and Performance, 21,* 876–900.

Seidenberg, M. S., & McClelland, J. L. (1989). A distributed, developmental model of word recognition and naming. *Psychological Review, 96,* 523–568.

Snodgrass, J. G., & Mintzer, M. (1993). Neighborhood effects in visual word recognition. *Memory & Cognition, 21,* 247–266.

Appendix A

Words Used in Experiment 1 and Sentences Used in Experiment 2

The words used in Experiment 1 appear in brackets in the middle of the sentences, and the word with higher frequency neighbors is listed first. The words in italics enclosed by brackets at the end of the sentences are the higher frequency neighbors of the first member of the pair.

The store didn't sell John's favorite [spice, sauce] any more. [*space*]
Everything was clean except for one [plate, spoon] that had egg on it. [*place*]
She was delighted to see the first [daisy, poppy] coming up in her garden. [*daily*]
It took a lot of effort, but the old [stove, dryer] was finally fixed. [*store*]
The gift he liked most was the blue [shirt, scarf] from his girlfriend. [*short*]
She was surprised to see a young [stork, robin] fly by the window.[*stock*]
In six months, the price of [flour, wheat] had risen very little. [*floor*]
The tailor finished the fancy [shawl, tunic] that the star would wear. [*shall*]
Because of the sudden change in temperature, the [frost, steam] turned to water. [*front*]
The picture reminded him of the large [birch, aspen] tree in his front yard. [*birth*]
The troops were slowed down by the wide [marsh, canal] that was in their way. [*march*]
The bullet hit the woman in the [cheek, waist], but she wasn't seriously hurt. [*check*]
He was appalled to see a [stone, brick] come flying through the window. [*store*]
After twenty years on the job, the [miner, flyer] was suddenly out of work. [*minor*]
When the children saw the picture of the [whale, camel] in their book, they laughed. [*while*]

The prince usually went to his beautiful [manor, villa] in the summer. [*major*]
The children liked the [chick, puppy] best of all the animals at the farm. [*check*]
The award was given to the [mayor, pilot] with the longest record of service. [*major*]
The settlers were glad to see a [rider, scout] who told them that the path was safe. [*river*]
The best place for buying [bread, fruit] is the little market on the corner. [*broad*]
In order to be safe, he placed the [torch, jewel] out of reach. [*touch*]
The pain coming from his [ankle, tooth] was almost unbearable. [*angle*]
To make way for the new [track, route], the workers had to blast through solid rock. [*truck*]
Learning to tie a [noose, lasso] is harder than it looks. [*noise*]
The old house had an unbelievable amount of [filth, urine] on the bathroom floor. [*fifth*]
The two month [truce, siege] was broken by a surprise attack. [*trace*]
David thought that [prose, verse] allowed him to express himself best. [*prove*]
At the conference, the major [theme, focus] was the role of women in society. [*there*]
It was cold because of the [shade, draft], so he decided to put on a sweater. [*share*]
The naturalist encountered an immense [horde, swarm] of insects in the swamp. [*horse*]
Mary expressed her extreme [shame, anger] by turning beet red. [*share*]
The best part about the new play was the [verve, flair] with which it was acted. [*verse*]
From across the room, Jim couldn't see the [medal, label] on Sam's jacket very well. [*metal*]
The secretary didn't know where to put the large [carton, parcel] that was delivered. [*carbon*]
The corrupt official accepted a thousand dollars for the [ransom, pardon] of the prisoner. [*random*]
Because of the dim lighting, the [ballot, ticket] was very difficult to read. [*ballet*]
According to statistics, [stroke, cancer] is one of the leading causes of death. [*strike*]
John was very proud of the new [stripe, tassel] on his uniform. [*strike*]
In some parts of the world, continual [strife, famine] causes widespread misery. [*strike*]
He saw it as a distinct (threat, menace] when the burglar picked up a knife. [*throat*]
The large [crease, fringe] made ironing the dress much more difficult. [*create*]
On Sundays, he usually had a big [brunch, waffle] before going out to play golf. [*branch*]
Mary warned her son about playing with the [dagger, hammer] he just found. [*danger*]
The high point of their trip was the beautiful [castle, mosque] that they saw in Spain. [*cattle*]
The car pulled up to the elegant [resort, casino] in the mountains. [*report*]
The only thing left in the desk was a blue [string, marble] in the bottom drawer. [*strong*]

Appendix B

Pseudowords Used in Experiment 1

vowal	prory	idiam	quall	bamon	resen	hafen	vexus	rimal	juire	themb	iroty
glofe	varor	blant	strow	nunse	deray	churm	cload	slape	guire	noime	spave
prome	stuke	brank	chole	shart	slite	stige	leate	clome	valne	prame	beeth
ottar	waner	blonk	romer	smick	morel	imoge	prine	wreng	stunf	brend	grote
thyse	panly	nyton	fluse	adoge	menon	dumty	julor	metel	phose	mosel	famor
cress	munth	swass	scole	trenk	nasal	debect	palame	nogice	merter	silmer	orasge
garlen	flomer	marnel	montey	tra fle	stible	buthon	bearon	chrode	ribban	arcode	carpot
coledy	delime	entyly	heasen	denade	piscol	monion	leston				

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