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The Effects of "Neighborhood Size" in Reading and Lexical Decision

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The effects of *neighborhood size* ("N")—the number of words differing from a target word by exactly 1 letter (i.e., "neighbors")—on word identification was assessed in 3 experiments. In Experiments 1 and 2, the frequency of the highest frequency neighbor was equated, and N had opposite effects in lexical decision and reading. In Experiment 1, a larger N facilitated lexical decision judgments, whereas in Experiment 2, a larger N had an inhibitory effect on reading sentences that contained the words of Experiment 1. Moreover, a significant inhibitory effect in Experiment 2 that was due to a larger N appeared on gaze duration on the target word, and there was no hint of facilitation on the measures of reading that tap the earliest processing of a word. In Experiment 3, the number of higher frequency neighbors was equated for the high-N and low-N words, and a larger N caused target words to be skipped significantly more and produced inhibitory effects later in reading, some of which were plausibly due to misidentification of the target word when skipped. Regression analyses indicated that, in reading, increasing the number of higher frequency neighbors had a clear inhibitory effect on word identification and that increasing the number of lower frequency neighbors may have a weak facilitative effect on word identification.

The impressive speed of the visual recognition of words implies that the processes responsible for selecting the correct lexical entry from the thousands of words stored in the lexicon are highly efficient. In spite of the efficiency of this process, there is a growing body of data that indicates that the printed word does not directly find its entry in a mental lexicon. Instead, these data suggest that, after the presentation of a visual word, similarly spelled words (the so-called "neighbors") become partially activated and affect the speed of lexical access (e.g., Andrews, 1989, 1992; Carreiras, Perea, & Grainger, 1997; Forster & Shen, 1996; Grainger & Jacobs, 1996; Grainger, O'Regan, Jacobs, & Segui, 1989, 1992; Johnson & Pugh, 1994; Paap & Johansen, 1994; Perea & Pollatsek, 1998; Sears, Hino, & Lupker, 1995; Snodgrass & Mintzer, 1993). Virtually all of these experiments have adopted Coltheart, Davelaar, Jonasson, and Besner's (1977) simple definition of an orthographic *neighbor*—any word that can be created by changing one letter of the stimulus word while preserving letter positions (e.g., *horse* and *mouse* are orthographic neighbors of *house*)—and have defined the *neighborhood* of a word to be the set of neighbors of that word. The design of the standard experiment in this area is to examine two sets of words that are equated on variables such as length and frequency in the language, but that differ on some neighborhood measure, and examine whether lexical decision time (or some other putative measure of lexical access time) differs between the two sets of words. Although there is growing agreement that a word's neighbors affect processing times in these tasks, there is often considerable controversy about whether such effects are facilitative or inhibitory and the interpretation of such effects.

Perhaps the most studied neighborhood variable is *neighborhood size* (which is sometimes referred to as N), which is the number of words in the neighborhood of a target word. Intuitively, and in many of the current models of word identification, increasing the size of the neighborhood could have both facilitative and inhibitory effects. First, consider the argument for facilitation (Andrews, 1989, 1992; Sears et al., 1995). In this view, the neighbors of the presented visual word are partially activated, and the presence of neighbors speeds lexical access either 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 or through reverberatory activity between the letter level and the word level.

Many of the experiments using the lexical-decision task provide data that are consistent with this view, as words with more neighbors are usually classified more rapidly as words than words with fewer neighbors, and with fewer errors (e.g., Andrews, 1989, 1992; Carreiras et al., 1997; Forster & Shen, 1996; Huntsman & Lima, 1996; Johnson & Pugh,

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1994; Laxon, Coltheart, & Keating, 1988; Perea, 1993; Sears et al., 1995; but see Coltheart et al., 1977). This effect does not appear to be due to an encoding advantage for words with more neighbors that contain frequently occurring letter combinations (e.g., positionally coded bigram frequency, as suggested by Grainger, 1992), because neighborhood size effects still occur when words are equated on measures of positional redundancy (Andrews, 1992). Moreover, manipulations of positional redundancy (bigram frequency) do not appear to have a significant effect, at least in lexical decision and naming (Andrews, 1992). However, the facilitative effects of neighborhood size obtained with word stimuli in the lexical-decision task (see Andrews, 1989, 1992; Grainger & Jacobs, 1996) are sensitive to word frequency (effects are stronger with lower frequency words than with higher frequency words). Similarly, several studies have consistently found facilitative effects of neighborhood size for low-frequency words in the standard naming task (e.g., Andrews, 1989, 1992; Peereman & Content, 1995; Perea & Carreiras, 1996; Sears et al., 1995).

As one might expect, there is controversy over whether these facilitative effects are indexing the speed of lexical access or, instead, are reflections of a different, task-specific process. One finding that causes some problem for a speeded, lexical-access view is that increasing the number of neighbors of a nonword in the lexical-decision task slows correct responses to these nonwords and causes more errors (Andrews, 1989, 1992; Coltheart et al., 1977; Forster & Shen, 1996; Johnson & Pugh, 1994; Laxon et al., 1988; Perea, 1993; Sears et al., 1995). If a greater number of neighbors merely enhances the identification of component letters, one would expect that its effect on nonwords would be facilitative rather than the observed inhibitory effect. In contrast, a relatively simple decision mechanism can explain these opposite effects parsimoniously. If we assume that the presence of many neighbors produces increased general excitation in the lexicon and that this excitation helps to bias the response in the lexical-decision task to "yes" (i.e., "word."), then we would expect that yes decisions to words with many neighbors would be facilitated, but that "no" decisions to nonwords with many neighbors would be inhibited. Further evidence that the facilitative effect in the lexical-decision task may be contaminated by such a decision-biasing effect is that the effect of neighborhood size differs with the type of nonword that is used as a distractor (the effect is weaker with wordlike nonwords) and task instructions that stress speed versus accuracy (the effect is weaker when accuracy is stressed). These differences make sense if one assumes that the decision-biasing mechanism has a stronger effect when lexical access is incomplete.

Further, a facilitative effect of increasing N in the naming task can be explained in terms of phonological or articulatory processes specific to this task rather than processes related to the identification of words. It may reflect the degree of consistency of the pronunciation of the orthographic rime (e.g., Grainger, 1992; Jared, McRae, & Seidenberg, 1990; Treiman, Mullennix, Bijeljac-Babic, & Richmond-Welty, 1995), and the initial sound may be generated before lexical access has taken place (Frederiksen & Kroll, 1976; Paap, McDonald, Schvaneveldt, & Noel, 1987), so that a complete pronunciation may not be assembled before the onset of naming. In fact, neighborhood size effects in naming are similar for low-frequency words and pseudowords (Peereman & Content, 1995; Perea & Carreiras, 1996), which also suggests that nonlexical factors play a role in the naming task. Thus, it seems that there are problems with assuming that lexical decision and naming latencies are good indexes of the effects of orthographic neighbors on the process of visual word recognition.

Above, we have indicated how increasing the size of the neighborhood could facilitate lexical access. However, there is an equally plausible mechanism for how it could inhibit lexical access. For example, in a search or verification model (e.g., the search model of Forster, 1976, or the activation-verification model of Paap, Newsome, McDonald, & Schvaneveldt, 1982), one could posit that lexical access is composed of two stages: activation of a *candidate set* (i.e., the set of neighbors) followed by a *verification stage,* which involves a search through the candidate set to find the actual lexical entry. In such a model, the second stage of lexical access clearly would be slowed down by having to search for the correct lexical item among a greater number of competing candidates (i.e., neighbors). These models differ as to whether they predict a facilitative effect of increasing neighborhood size on the first stage; however, they view the latter stage as the time-consuming step, and so the overall process of lexical access is predicted to be slowed.[1] In activation models, such as the interactive-activation model (McClelland & Rumelhart, 1981) in which the activation of candidates and mutual inhibition among candidates occurs in a single stage and in parallel, the prediction of whether increasing neighborhood size is inhibitory or facilitative depends on assumptions about the combinations of parameters used in the simulations. For example, the simulations with the interactive-activation model reported by Jacobs and Grainger (1992)—using the default parameters given by McClelland and Rumelhart (1981)—showed inhibitory effects of neighborhood size, whereas Coltheart and Rastle (1994) reported facilitative effects of neighborhood size with a different set of parameters (most notably, lower mutual competition among lexical candidates).

In fact, inhibitory effects of neighborhood size have been obtained in other identification paradigms that are designed to tap lexical access (Carreiras et al., 1997; Perea, 1993; Snodgrass & Mintzer, 1993; van Heuven, Dijkstra, & Grainger, 1998; Ziegler, Rey, & Jacobs, 1998). For example, consider the experiments of Snodgrass and Mintzer (1993). They used the words of Andrews (1989) in a series of perceptual identification and speeded identification tasks. In their perceptual identification task (Experiments 3 and 4), the participants were presented with a target word that was moderately visually degraded. Sometimes the target was

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[1] However, the current version of the search model (Forster & Shen, 1996) does not appear to predict any effects of neighborhood size or neighborhood frequency for words because the evaluation process is carried out according to a goodness-of-fit criterion rather than word frequency.

preceded by brief presentations of three more degraded versions of the words (in a sequence of decreasing degradation), and participants' accuracy of identification was measured. In their speeded identification task (Experiment 5), participants were presented with an ascending series of fragmented images, each presented for a fixed duration, and the participants had to press a response key as soon as they recognized the word. In both tasks, an inhibitory effect of neighborhood size was found. Similar findings have been obtained in the *progressive demasking* task (see Grainger & Segui, 1990), in which the target word and a pattern mask are presented in successive cycles, with the duration of the mask decreasing and the duration of the target word increasing (see Carreiras et al., 1997; Perea, 1993). Participants simply have to press a response key as soon as they recognize the word and then name it. The percentage of errors in this task is typically very low, so that the participants' button-push response does not appear to be the result of guessing.

In sum, there are no clear conclusions that one can draw about the effect of neighborhood size on lexical access. The facilitative effects in the lexical-decision task can be ascribed to processes other than identification of the printed word, whereas the inhibitory effects in a task in which a degraded stimulus is presented could be ascribed to guessing processes that are not important when normal, nondegraded stimuli are presented. Another problem with assessing the effects of neighborhood size is that the frequency of the neighbors has been shown to be a relevant factor in many of these tasks, although there is, again, some disagreement about the nature of the neighborhood-frequency effect. In these experiments, two sets of words are compared (one having no higher frequency neighbors and the other having several higher frequency neighbors), with the size of the neighborhood, word frequency, and word length equated for the two sets. A search or verification model, in which the search is frequency ordered, clearly predicts that having higher frequency neighbors will delay lexical access. A parallel, interactive-activation model also predicts inhibition if the degree of activation of candidates is dependent on their frequency (because of lateral interference at the word level).

Again, the data are not completely consistent, but the evidence favors the conclusion that having higher frequency words inhibits lexical access. An inhibitory effect of neighborhood frequency has been found in several lexical-decision studies (Carreiras et al., 1997; Grainger & Jacobs, 1996; Grainger et al., 1989, 1992; Grainger & Segui, 1990; Huntsman & Lima, 1996; Perea & Pollatsek, 1998), although some other studies have obtained null effects (Forster & Shen, 1996; Sears et al., 1995). In addition, inhibitory effects of neighborhood frequency have been obtained in speeded identification tasks (Carreiras et al., 1997; Grainger & Segui, 1990; Perea, 1993) and in two eye-movement studies (Grainger et al., 1989; Perea & Pollatsek, 1998). In the former, participants made semantic-relatedness judgments on a pair of words, and the reading time for the first word was the dependent variable. In the latter, pairs of target words, one with no higher frequency neighbors and one with at least one higher frequency neighbor, were embedded in the same sentence frame, and fixation times in and near the target word region were compared. The fact that inhibitory effects have been obtained in a wide variety of tasks (including a natural reading task) strongly suggests that the inhibitory effect of neighborhood frequency is not likely due to some uninteresting factor that is limited to laboratory tasks.

The fact that there are inhibitory effects of neighborhood frequency raises the question of whether uncontrolled effects of neighborhood frequency are causing part or all of the neighborhood size effects discussed above. In fact, the question of how to control neighborhood frequency when varying neighborhood size is not clear. What does one keep constant—the mean frequency of the neighbors, the frequency of the highest frequency neighbor, or something else? In the lexical-decision task, the problem may not be severe because several studies (Grainger, 1990; Grainger et al., 1989; Grainger & Jacobs, 1996; Huntsman & Lima, 1996; Perea & Pollatsek, 1998) have observed that the inhibitory effect on lexical decisions was no greater when there were several higher frequency neighbors than when there was only one higher frequency neighbor (i.e., the neighborhood-frequency effect is not cumulative). If so, then equating the frequency of the highest frequency neighbor should provide a good control for frequency effects when examining the effects of neighborhood size. However, the effect of neighborhood frequency seems to be cumulative in speeded identification tasks (Grainger & Jacobs, 1996) and probably in reading (Perea & Pollatsek, 1998); that is, there is more inhibition from several higher frequency neighbors than from one. This raises the possibility that it will be difficult to study neighborhood size effects in these tasks without some other control on neighborhood frequency.

Another possibility is that one has to consider the effects of higher and lower frequency neighbors separately (Paap & Johansen, 1994). Interestingly, when the number of higher frequency neighbors is controlled in the lexical-decision task, facilitative effects of neighborhood size have been obtained (Carreiras et al., 1997; Forster & Shen, 1996; Perea, 1993; Sears et al., 1995), which means that the number of lower frequency neighbors is facilitative in this task (in contrast to the noncumulative effect of number of higher frequency neighbors).[2] As a result, the facilitative effects of neighborhood size in the studies that did not control for neighborhood frequency (e.g., Andrews, 1989, 1992) may have been caused by an increasing number of lower frequency neighbors. Paap and Johansen's (1994) regression analysis of Andrews's (1992) data suggested that this was the case, because there were facilitative effects of neighborhood size that were due to the number of neighbors when the influence of the number of higher frequency neighbors was partialed out; that is, when the influence of

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[2] For example, in the study of Perea and Pollatsek (1998), there was a significant correlation between the number of lower frequency neighbors and the reaction time when the effects of factors such as Word Frequency, Number of Higher Frequency Neighbors, Number of Letters, and Number of Syllables were partialed out.

the number of higher frequency neighbors was partialed out, the remaining variance reflected essentially the number of lower frequency neighbors.

The main goal of this investigation was to shed more light on the role of the number of neighbors in word identification by embedding the target words in a normal, sentence-reading task. As in the study by Perea and Pollatsek (1998), participants read the sentences while their eye movements were monitored, and fixation times on words in the target word region were used to examine the effects of the experimental manipulation. However, as in Perea and Pollatsek, we also wanted to study the same words in a laboratory word-identification task for comparison purposes. As in the former study, we chose the lexical-decision task because it has been studied most intensively. An additional reason for using the reading task to investigate neighborhood size (besides the ecological validity) is that it offers a window on whether the effects observed occur relatively early or late in word identification. Because eye fixations in reading are relatively short (usually about 200–250 ms), one can examine whether effects are early (e.g., on the first fixation on the target word), intermediate (e.g., on later fixations on the target word), or late (e.g., on fixations after the target word has been left or on regressions back to the target word). A recent model of eye movements in reading (Reichle, Pollatsek, Fisher, & Rayner, 1998; see also Pollatsek & Rayner, 1990), which we discuss later, is a tool for making more theoretical conclusions from the eye-movement record.

In Experiments 1 and 2, we controlled for neighborhood frequency, in the sense that all target words had at least one higher frequency neighbor and the frequencies of the highest frequency neighbor were equated. As indicated above, this control may be appropriate for lexical decision because the neighborhood-frequency effect in this task does not appear to be cumulative (instead, there are suggestions that adding more high-frequency neighbors could be facilitative; see Sears et al., 1995). In reading tasks, however, the effect of neighborhood frequency appears to be cumulative (see above), in the sense that words with several higher frequency neighbors were identified more slowly than those with only one higher frequency neighbor. In the Perea and Pollatsek (1998) study, the correlation of the number of higher frequency neighbors with gaze duration was reliable ($r = .24, p < .03$) for the words that had at least one higher frequency neighbor, when the effects of factors such as Number of Lower Frequency Neighbors, Word Frequency, Number of Letters, and Number of Syllables were partialed out. There was also a significant facilitative effect found for the number of lower frequency neighbors in this analysis ($r = -.38, p < .01$). (However, it should be noted that these two effects, although present, were much weaker when all the words in the experiment—both those with higher frequency neighbors and those without higher frequency neighbors—were entered into the analyses.) These findings suggest that there is no magic control for neighborhood frequency. As a result, Experiment 3 and regression analyses in all three experiments are directed toward disentangling the effects of higher and lower frequency neighbors in visual word recognition.

Experiment 1

The design of this lexical-decision experiment is straightforward. There were two sets of words that differed in the number of neighbors but that were equated on word frequency, word length (i.e., number of letters), and the frequency of the highest frequency neighbors. (All the words had a higher frequency neighbor that had a frequency of 50 or more per million words). We stressed the accuracy of the responses over speed to the participants to avoid shallow processing of the stimuli (e.g., Grainger & Jacobs, 1996; Paap & Johansen, 1994; Snodgrass & Mintzer, 1993).

Method

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

Design and materials. The 80 target words (see Appendix A) were either four or five letters in length (40 were four-letter words and 40 were five-letter words). All the target words had frequencies of 34 or less per million in the Kučera and Francis (1967) count, and all had higher frequency neighbors. The number of neighbors (N value) for the target words varied from 1 to 17. The 80 target words were divided into 40 matched pairs; in each pair, the 2 words were matched on length, approximately matched on frequency, but differed in N. The two sets of 40 words that resulted were fairly closely matched in the frequency of the target word and frequency of the highest frequency neighbor. However, the words with more neighbors also had more higher frequency neighbors (see Table 1 for the characteristics of the target words).

A set of 80 orthographically legal nonwords used for the lexical-decision task was created by changing a middle letter in words of similar length. The words that were used to create the nonwords were from the same pool as the experimental words; they

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

Neighborhood size	Word frequency (per million)[a]	Neighborhood size (Coltheart N)[a]	No. of higher frequency neighbors[a]	Mean frequency of highest frequency neighbor[b]
Words with many neighbors	8.6 (8.9)	8.5 (2.8)	4.0 (2.3)	345 (183)
Words with few neighbors	7.4 (8.7)	2.2 (0.8)	1.5 (0.6)	409 (154)

[a] Values are means, with standard deviations in parentheses. [b] Values are means, with medians in parentheses.

were not used as word stimuli because it was difficult to find the appropriate matched words for them that were needed in Experiment 2. Each participant saw all of the 80 target words and the 80 nonwords.

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 2.28° and 2.66° of visual angle, respectively.

Procedure. Participants were tested individually in a quiet room. Presentation of the stimuli and recording of latencies were controlled by an IBM-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 blank, interstimulus interval, a lowercase letter string (either a word or a nonword), also centered on the screen, was presented until the participant made a 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. Participants were instructed to make their responses as quickly and as accurately as possible; however, accuracy was stressed to avoid shallow processing of the stimuli. The intertrial interval was 1.5 s. Each participant received 24 practice trials prior to the 160 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

For the word stimuli, the trials in which there were incorrect responses (169 observations, or 8.1% of the total) and reaction times greater than 1,500 ms or less than 300 ms (25 observations, or 1.2% of the total) were removed from the response-time analyses. (The percentage of errors on the nonword targets was 7.1%.) All responses to the target word *aria* were also discarded from the analysis because it was classified as a nonword 80% of the time. Our primary focus was on the mean response times for the words, and these were assessed for reliability over both subjects (F_1) and items (F_2). Because of the matched design, neighborhood size was treated as a within-item variable in the item analyses.

There was a facilitative effect of 26 ms for having many neighbors (605 ms for the words with few neighbors vs. 579 ms for the words with many neighbors), $F_1(1, 25) = 26.44$, $MSE = 333, p < .001$; $F_2(1, 38) = 4.99, MSE = 2{,}692, p < .04$. For the error data, the N effect was also significant in the analysis by participants, $F_1(1, 25) = 7.47, MSE = 18.9, p < .02$; $F_2(1, 38) = 3.04, MSE = 63.7, p = .09$. The error rates were 8.9% for the words with few neighbors and 6% for the words with many neighbors.

As indicated earlier, prior research suggested that the facilitative effect of neighborhood size in the lexical-decision task might be caused primarily by the number of lower frequency neighbors rather than by the number of higher frequency neighbors. To test that hypothesis, we examined the effect of the number of lower frequency neighbors in a multiple regression analysis. In this analysis, lexical-decision latency was the dependent variable and the number of lower frequency neighbors, the number of higher frequency neighbors, the log of frequency of the word, the mean positional bigram frequency, the number of letters, and the number of syllables were used as predictors. The regression analysis indicated that each additional low-frequency neighbor reduced lexical-decision time by 5 ms, $t(73) = 1.86$, $p = .098$, but that each additional high-frequency neighbor increased lexical-decision time by 3 ms (but $t < 1.00$). There was also a significant effect of log frequency, $t(73) = 3.43, p = .001$.

Experiment 2

In Experiment 1, we essentially replicated earlier work using the lexical-decision task. We demonstrated that the presence of many neighbors facilitates "word" decisions in a lexical-decision task. Moreover, the regression analyses suggested that this was because the facilitative effects of having lower frequency neighbors dominated the inhibitory effects of having higher frequency neighbors. We next wanted to determine whether the same neighborhood size effect would be observed with the same words when people were engaged in silent reading as opposed to making lexical-decision judgments.

The extension of Experiment 1 was relatively straightforward. We constructed 40 sentence frames, one for each matched pair of target words. As a result, each frame produced two sentences, one containing the target word with few neighbors and the other containing the target word with many neighbors (both in the same location in the sentence). Somewhat surprisingly, it was not hard to embed the 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 many neighbors was easier to read than the sentence containing the word with few neighbors. Of particular interest was 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-six students from the University of Massachusetts at Amherst took part in the experiment in exchange for course credit or for money. None of the students 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 40 pairs of sentences (see Appendix A) that used the 80 target words of Experiment 1. The two members of each sentence pair were identical except for the target word (one target word having few neighbors and the other having many neighbors). Each sentence was no more than 80 character spaces in length, occupying one line on the cathode-ray-tube (CRT) display screen; the target word was usually somewhere in the middle of the sentence and was never the first or last word of the sentence.

Design. Two lists were created, each containing 40 experimental sentences and 20 filler sentences. Each list contained 20 sentences with a target word that had few neighbors and 20 sentences with a target word that had many neighbors. The presence of the target words was counterbalanced across the two lists, so that if a word with many neighbors (e.g., *wand*) appeared in one list, its corresponding target word with few neighbors (*icon*) 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. Each participant saw one of the two lists, and the order of the experimental sentences was randomized independently for each participant. Before reading the experimental sentences, each participant completed eight trials with practice sentences to become familiar with the procedure.

To ensure that differential ease of the target words fitting into the sentential context was relatively balanced, we conducted a rating study in which 15 other participants saw the 40 pairs of sentences and were asked to rate the relative naturalness of the two sentences. They could respond either that the sentence with the low-N word was more natural, that the sentence with the high-N word was more natural, or that they were equally natural. (Of course, they were not told which word was high N, and the order of the two sentences in a pair was randomized.) We coded the three categories as 1, −1, and 0, respectively, and used the mean of these ratings for a given sentence as the measure of differential naturalness. Over the 38 pairs that were used in the analyses,[3] the mean value for this measure was −.035 (*SD* = .457), which indicates that the sentences, on average, were almost perfectly balanced in terms of the words fitting into the sentence. As a result, we are quite confident that differences between the conditions can be ascribed to differential ease of lexical access.

Apparatus. Eye movements were recorded by a Fourward Technologies Dual Purkinje Eyetracker, which has a resolution of less than 10 min of arc and the output is linear over the angle subtended by a line of text. The eye tracker was interfaced with an ACI 486 computer. The position of the eye was sampled every millisecond, and each 4 ms of eye-tracker output was compared with the output of the previous 4 ms to determine whether the 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 equaled 1° of visual angle. Viewing was binocular, but eye movements were recorded from the participant's right eye. A bite-bar was used to eliminate head movements in the experiment.

Procedure. When a participant arrived for the experiment, a bite-bar was prepared and the eye-tracking system was calibrated. The calibration period usually lasted less than 5 min. After the calibration was completed, participants were told that they would be given sentences to read and 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, they were asked to answer comprehension questions about the sentence they had just read after 25% of the sentences. Participants had little difficulty answering the questions correctly.

Data analysis. Several dependent variables were of major interest. The first group was 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 were counted only when the reader initially fixated the word with a forward saccade; moreover, the measures were conditional (i.e., the averages were 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. This included *spillover,* the duration of the first fixation after leaving the target word, the probability of making a regression back to the target word, and the total time spent on the target word (i.e., the sum of all fixation durations on the target word including regressive fixations).

Table 2
Eye-Movement Measures for the Target Words in Experiment 2 as a Function of Neighborhood Size

Measure of reading	Words with few neighbors	Words with many neighbors	Difference
First-fixation duration on target word	278 ms	289 ms	−11 ms
Gaze duration on target word	297 ms	321 ms	−24 ms
Probability of skipping target word	15.9%	13.6%	2.3%
Duration of first-fixation after target word	265 ms	267 ms	2 ms
Percent of regressions back to target word	11.0%	15.5%	−4.5%
Total time on target word	332 ms	383 ms	−51 ms

Results

A small number of sentences were excluded from the analysis because of problems with monitoring the eye movements: 7.6% of the trials were eliminated either because there was a track loss while reading the sentence or because 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, with neighborhood size as a within-item variable in the item analyses.

First-pass measures. Unlike in the lexical-decision task, the effect of increasing N was inhibitory in reading. This inhibitory effect showed up even in the first-pass measures, although it was significant only in the gaze-duration measure (see Table 2). First, target words with many neighbors were skipped 2.3% less often than the target words with few neighbors (although both Fs < 1.00). Second, the mean first-fixation duration on target words with many neighbors was 11 ms greater than that for target words with few neighbors, $F_1(1, 25) = 3.79$, $MSE = 397$, $p < .07$; $F_2(1, 37) = 2.39$, $MSE = 922$, $p = .13$. Third, the mean gaze duration on target words with many neighbors was 24 ms

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[3] Due to an error in creating the stimulus lists, one of the sentence pairs contained two words from large neighborhoods: *liver* and *shell* (in Experiment 1, the list correctly contained the low-N word *coral* instead of *shell*). For that reason the pair *liver/shell* was not used in the analyses of variance (ANOVAs), although both words were used in the regression analyses. In fact, the context in which those words appeared was neutral: "In many ways the *liver/shell* is the most (. . .)." Additionally, the sentence pair containing *aria/tune* was not used in the ANOVA, as a number of participants were not familiar with the meaning of *aria* (only *tune* was used in the regression analysis). As a result, 79 words were used in the regression analyses, whereas 76 words were used in the ANOVAs.

greater than that for target words with few neighbors, $F_1(1, 25) = 10.38$, $MSE = 698$, $p < .004$; $F_2(1, 37) = 6.34$, $MSE = 1{,}577$, $p < .02$. Thus, there was no indication of any facilitative effect of increasing neighborhood size in these early measures and a clear indication of inhibition by the time the word had been left.

Later measures and cumulative measures. Chronologically, the first measure of processing after the reader leaves the target word is the duration of the first fixation after leaving the target word (spillover). This measure is often "noisy" because this fixation could be either on the word following the target word or the word following that. The effect of increasing neighborhood size was inhibitory, although quite small (2 ms) and obviously not significant (both Fs < 1.00). A second late measure of processing difficulty on the target word is the probability of regressing back to the target word. Again, the effect of increasing neighborhood size was inhibitory, as readers regressed back to the target word 4.5% more often when the target words had many neighbors, although this effect was again not statistically significant, $F_1(1, 25) = 2.76$, $MSE = 95.4$, $p < .11$, and $F_2(1, 37) = 1.51$. A cumulative measure of target-word processing that includes both first and second pass times is the total time spent on the target word: Readers' total times were 51 ms longer on the target words when they had many neighbors, $F_1(1, 25) = 19.38$, $MSE = 1{,}738$, $p < .001$, and $F_2(1, 37) = 13.68$, $MSE = 3{,}128$, $p < .001$.

In sum, the effect of increasing neighborhood size in the reading task was consistently inhibitory. Suggestions of the inhibition occurred even before the target word was fixated, as readers skipped target words that had more neighbors slightly less often than the target words that had fewer neighbors. There was a clear inhibitory effect on gaze duration (it was 24 ms longer on the target words with many neighbors), and there were even clearer effects on the total time spent on the target word (it was 51 ms longer on the target words with many neighbors). Thus, it appears that if there is a facilitative effect of having more neighbors, it is swamped by an inhibitory effect at all stages of processing that can be detected by eye-movement measures.

Regression analyses. The overall effect of increasing neighborhood size was clearly inhibitory. Experiment 2 of Perea and Pollatsek (1998) indicated that increasing the number of higher frequency neighbors was inhibitory, and thus it is likely that the inhibitory effect of increasing neighborhood size observed in the current experiment was due to increasing the number of higher frequency neighbors. Thus, there is the possibility that there is a latent facilitative effect of increasing the number of lower frequency neighbors that is masked by this inhibitory effect. We assessed this possibility by doing multiple regression analyses on the various dependent variables, with number of higher frequency neighbors, number of lower frequency neighbors, log of word frequency, the mean positional bigram frequency, the number of letters, and the number of syllables as predictors. These analyses confirmed the hypothesis that increasing the number of higher frequency neighbors had an inhibitory effect in the reading task. Each additional higher frequency neighbor increased first-fixation duration by 4 ms, $t(73) = 1.69$, $p = .095$; gaze duration by 7 ms, $t(73) = 2.57$, $p = .012$; spillover duration by 3 ms, $t(73) = 1.66$, $p = .010$; total time by 10 ms, $t(73) = 2.27$, $p = .027$; decreased skipping of the target word by 0.5%, $t(73) \approx 1.00$; and increased the probability of regressing back to the target word by 0.7%, $t(73) \approx 1.00$. This inhibitory effect appeared to mask a weak facilitative effect of the number of lower frequency neighbors. Each additional lower frequency neighbor decreased first-fixation duration by 0.7 ms, $t(73) < 1.00$; gaze duration by 0.6 ms, $t(73) < 1.00$; spillover duration by 3 ms, $t(73) = 1.81$, $p = .075$; and total time by 0.6 ms, $t(73) < 1.00$; and increased skipping of the target word by 0.6%, $t(73) = 1.23$, $p > .20$, and had virtually no effect on the probability of regressing back to the target word, $t(73) \approx 0$. The only other findings of interest from the regression analyses were that increasing word frequency had a facilitative effect on the dependent measures, although this was significant only for gaze duration, $t(73) = 2.14$, $p = .036$, and that the four-letter words were skipped more often than the five-letter words, $t(73) = 2.00$, $p = .050$.

Given the cumulative influence of the number of higher frequency neighbors in reading, it appears that the inhibitory results found in Experiment 2 are due to neighborhood frequency rather than to neighborhood size (N). The regression analyses of the data of Experiment 2 suggested, albeit weakly, that increasing N without increasing the number or frequency of higher frequency neighbors may have a facilitative effect on at least some stages of word identification. In Experiment 3, we assessed this possibility directly by holding the frequency and number of higher frequency neighbors constant and varying the number of lower frequency neighbors of pairs of target words in a reading experiment. We thought that another lexical-decision experiment was unnecessary because Experiment 1 had obtained a facilitative effect on lexical-decision times when the number of neighbors increased in spite of the fact that the number of higher frequency neighbors also increased.

Experiment 3

Method

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

Materials. The stimuli were a set of 28 pairs of sentences (see Appendix B). The two members of each pair were identical except for the target word (one target word having few neighbors and the other having many neighbors). Two of the pairs were four-letter words, and the other 26 pairs were five-letter words. Each stimulus sentence was no more than 80 character spaces in length, occupying one line on the CRT display screen. As in Experiment 2, we conducted an independent rating study in which participants were asked to judge the relative naturalness of each pair of sentences. The procedure was the same as in Experiment 2, and the coding system we used was the same (i.e., "1" for the low-N word and "−1" for the high-N word). Again, the naturalness of the sentences was quite well matched, as the mean rating over the 28 sentence pairs was 0.007 ($SD = 0.448$).

Design. The design was identical to that of Experiment 2 except for the different number of sentences and the fact that the manipulation of neighbor size was somewhat different. Two lists were created, each containing 28 experimental sentences and 78 filler sentences, and each participant saw one of the two lists. Each list contained 14 experimental sentences with a target word with few neighbors and 14 experimental sentences with a target word with many neighbors. The presence of the target words was counterbalanced across the two lists, so that if a word with many neighbors (e.g., *crane*) appeared in one list, its corresponding target word with few neighbors (*cargo*) 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 (see Table 3). The apparatus, procedure, and data analyses were identical to those in Experiment 2.

Results

A small number of sentences were excluded from the analysis because of problems with monitoring the eye movements: 4% of the trials were eliminated either because there was a track loss while reading the sentence or because participants were not fixating where they were supposed to when the sentence appeared. As in Experiments 1 and 2, neighborhood size was treated as a within-item variable in the item analyses.

First-pass measures. The two measures of fixation time on the target word, first-fixation duration and gaze duration, showed little effect of the number of lower frequency neighbors (all Fs < 1). For gaze duration, however, the 5-ms difference (both Fs < 1) was in the direction of facilitation (see Table 4). The most striking difference between the two conditions in the early measures was in the percentage of times the target words were skipped: Words with many low-frequency neighbors were skipped 12% more often than words with few low-frequency neighbors in the participant data and 7% more often in the item data, $F_1(1, 23) = 22.72$, $MSE = 75, p < .001$, and $F_2(1, 27) = 4.34, MSE = 197, p < .05$. One interpretation of this result is that the words with many low-frequency neighbors were often identified parafoveally, which allowed them to be skipped. An alternative possibility, however, is that skipping may not necessarily be dependent on full lexical access but instead on a partial identification process (Reichle et al., 1998). We return to this issue after examining the rest of the data.

Table 4
Eye-Movement Measures for the Target Words in Experiment 3 as a Function of Number of Lower Frequency Neighbors

Measure of reading	Words with few low-frequency neighbors	Words with many low-frequency neighbors	Difference
First-fixation duration on target word	279 ms	281 ms	−2 ms
Gaze duration on target word	310 ms	305 ms	5 ms
Probability of skipping target word	11.6%	24.1%	−12.5%
Duration of first-fixation after target word	271 ms	268 ms	3 ms
Percent of regressions back to target word	8.1%	12.4%	−4.3%
Total time on target word	347 ms	373 ms	−26 ms

Later measures and cumulative measures. The first measure of later processing, the duration of the first fixation following the target word, also showed a small (3 ms) facilitative effect of increasing N that was far from reliable (both Fs < 1). The other two later measures, however, showed clear inhibitory effects of increasing neighborhood size: There were 4% more regressions back to the target word when it had many neighbors, $F_1(1, 23) = 4.94, MSE = 68, p < .05$, and $F_2(1, 27) = 5.01, MSE = 129, p < .05$; and readers, in total, spent 26 ms longer on the target word, given that they fixated on it, $F_1(1, 23) = 4.63, MSE = 2{,}346, p < .05$, and $F_2(1, 27) = 20.94$, $MSE = 1{,}876$, $p < .001$. However, even with the greater frequency of regressions back to the target words with more neighbors, readers fixated on those words less often (on either the first or second pass) than the words with fewer neighbors. Thus, from the above results, it is hard to say whether the net effect of increasing neighborhood size is facilitative or inhibitory.

Table 3
Characteristics of the Target Words in Experiment 3

Size of lower frequency neighborhood	Word frequency (per million)^a	No. of lower frequency neighbors^a	No. of higher frequency neighbors^a	Mean frequency of highest frequency neighbor^b
Words with many low-frequency neighbors	19.2 (13.3)	4.8 (1.0)	0.9 (1.0)	111 (25.5)
Words with few low-frequency neighbors	20.0 (12.0)	0.6 (0.5)	0.9 (1.0)	75 (21.5)

^{a}Values are means, with standard deviations in parentheses. ^{b}Values are means, with medians in parentheses.

As a result, we measured the mean total sentence-reading time in the two conditions, and the net effect of increasing neighborhood size was inhibitory (2,373 ms vs. 2,470 ms, for low- and high-N words, respectively), although the difference was not significant, $F_1(1, 23) = 3.56$, $p = .07$, $F_2(1, 27) = 2.19$, $p = .15$.

To summarize, the net effect of increasing the number of low-frequency neighbors appears to be weakly inhibitory, although there was a facilitative effect early in processing. This is in contrast to the data of Experiment 2, in which increasing the total number of neighbors (which was confounded with increasing the number of high-frequency neighbors) produced no facilitative effects and significant inhibitory effects as early as gaze duration. The facilitation in Experiment 3 appeared almost exclusively as a large difference in the probability of skipping the target word. (The regression analyses in Experiment 2 also indicated that a larger number of lower frequency neighbors produced higher skipping rates, although the effect was much smaller, about 0.5% additional skips per additional low-frequency neighbor, and far from significant, $p > .20$.) The skipping effect was a bit peculiar, not only because it was so much bigger than in Experiment 2, but because other manipulations that produce such a large difference in skipping rate (e.g., differences in predictability and differences in word frequency) also produce quite substantial effects on first-fixation duration and gaze duration. Accordingly, we tried to understand the data more fully through regression analyses.

Regression analyses. The results of the multiple regression analyses were generally similar to those of Experiment 2. As in Experiment 2, the number of lower frequency neighbors, the number of higher frequency neighbors, the log frequency of the target word, the mean positional bigram frequency, the word length, and the number of syllables of the target word were used as predictors for the various dependent variables. As in Experiment 2, increasing the number of higher frequency neighbors had an inhibitory effect, with the notable exception of its effect on the probability of skipping the target word. Each additional higher frequency neighbor increased first-fixation duration by 9 ms, $t(49) = 1.51, p > .10$; gaze duration by 7 ms, $t \approx 1$; spillover duration by 3 ms, $t < 1$; and total time by 32 ms, $t(49) = 2.96$, $p = .005$; and increased the probability of regressing back to the target word by 5.5%, $t(49) = 2.56$, $p = .005$; however, it increased skipping of the target word by 4.6%, $t(49) = 2.19, p = .033$. Consistent with the above analyses of variance, the effects of increasing the number of lower frequency neighbors appeared to be weakly facilitative on early measures, except for the skipping rate, and weakly inhibitory on later measures. Each additional lower frequency neighbor had virtually no effect on first-fixation duration ($t \approx 0$), decreased gaze duration by 1.5 ms ($t < 1$) and spillover duration by 1 ms ($t < 1$), and increased skipping of the target word by 2.0%, $t(49) = 2.27, p = .028$, but increased the probability of regressing back to the target word by 0.9%, $t(49) = 1.20$, $p > .20$, and increased total time by 9 ms, $t(49) = 2.02$, $p = .049$. The only other findings of interest were that increasing log of word frequency had a facilitative effect on the dependent measures, although this was significant only for first-fixation duration, $t(49) = 2.44$, $p = .019$, and that the four-letter words were skipped more often than the five-letter words, $t(49) = 2.04, p = .047$.

Even though the inhibitory effects of the number of higher frequency neighbors on first-fixation duration, gaze duration, and spillover duration were not significant in the regression analyses of Experiment 3, they were numerically quite similar to the values obtained in Experiment 2. The lack of significance of these effects in Experiment 3 is likely due to the fact that this variable was controlled and, as a result, had little variability. The effects of the number of lower frequency neighbors on first-fixation duration, gaze duration, and spillover duration are similar to the analyses in Experiment 2 and confirm that if this variable has a facilitative effect on these measures, it is weak.

The most striking discrepancy between the analyses of the two experiments is that increasing the number of higher frequency neighbors appeared to increase the skipping rate substantially in Experiment 3, whereas in Experiment 2, increasing the number of higher frequency neighbors decreased the skipping rate (although the latter effect was quite small). A second discrepancy between the two analyses was that increasing the number of lower frequency neighbors in Experiment 3 appeared to have inhibitory effects on the second-pass measures of processing, the number of regressions, and the total time, whereas it had little effect on these measures in Experiment 2. Perhaps related to that, the number of higher frequency neighbors had even stronger inhibitory effects on these second-pass measures in Experiment 3, even though it should have had less predictive power because of a restricted range. A plausible hypothesis is that the inhibitory effects observed in the second-pass measures that were due to increasing the number of neighbors were, at least in part, a result of the increased skipping rates that were due to increasing the number of neighbors. If so, it suggests that these increased skipping rates that were modulated by neighborhood size may have been largely due to misidentification of the target word, which needed correction later in processing.

What word is being skipped? The most plausible hypothesis for such misidentification of the target word was that the readers may have tended to encode the target word as a higher frequency neighbor (most probably, the highest frequency neighbor) when it was seen parafoveally. To examine the plausibility of this hypothesis, we examined each sentence to determine whether the highest frequency neighbor was a reasonable continuation of the sentence. In fact, for 14 of the 28 pairs, the highest frequency neighbor of the high-N target word was a plausible continuation of the sentence. For the other 14 pairs, either the highest frequency neighbor was anomalous with the prior sentence context or no neighbor had a higher frequency than the target word.[4] (In

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[4] A norming task was given to 10 participants who were given booklets that contained beginning fragments of the experimental sentences that contained target words with higher frequency neighbors. The fragment contained the sentence up to and including the target region, except that the target word was replaced by

all 28 sentences, the sentence context eventually made the highest frequency neighbor anomalous.)

The results of these analyses were revealing. For the 14 sentences in which the highest frequency neighbor was not immediately anomalous, the increase in skipping rate for larger N words was 14% (30% vs. 16%), whereas for the other 14 sentences, the increase was only 2% (18% vs. 16%). It thus appeared that participants were often skipping the target word on the basis of at least a tentative identification of the target word as the highest frequency neighbor and that identification of this highest frequency neighbor was being facilitated by the presence of more lower frequency neighbors. If participants skipped the target word because of misidentifying it, one would expect a greater cost later on in those cases when the highest frequency neighbor had initially been plausible. In fact, that was what was observed. When the highest frequency neighbor initially fit in, participants regressed back to the higher N word 8% more (20% vs. 12%) and their total time was 73 ms greater (411 ms vs. 338 ms), whereas in the other cases, they regressed back to the higher N word only 5% more (13% vs. 8%) and their total time was only 32 ms greater (367 ms vs. 335 ms).

This partition, however, produced the opposite pattern on first-fixation durations and gaze durations that it did on skipping. That is, the facilitation effects for larger N words appeared only when the highest frequency neighbor did not fit or when no neighbor was a higher frequency than the target word (a 6-ms difference for first-fixation durations and a 12-ms difference for gaze durations) and not when the highest frequency neighbor fit into the sentence context (−1 ms for first-fixation durations and 0 ms for gaze durations). Thus, when the highest frequency neighbor did not fit into the context, and presumably the target word was correctly identified, it appeared that increasing the number of lower frequency neighbors did facilitate processing to some extent. It is also worth noting that when the same multiple regression analyses were performed on the target words from the 14 sentence frames in which the highest frequency neighbor did not fit in, the inhibitory effects of the number of higher frequency neighbors were large and significant on first-fixation duration, gaze duration, regressions, and total time, $ts(22) = 2.88$, 2.63, 4.42, and 4.83, and $ps = .009$, .015, .001, and .001, respectively.

Summary. Experiment 3 indicated that increasing the number of lower frequency neighbors of a word apparently had an initial facilitative effect. We say "apparently" because this was primarily indicated by a greater tendency to skip the target word, and subsidiary analyses indicated that this may have been largely due to misidentification of the target word as the highest frequency neighbor. However, there were also suggestions of facilitative effects on first-fixation duration and gaze duration that were not plausibly due to such misidentification. Overall, these initial facilitative effects of increasing the number of low-frequency neighbors were offset by later costs, indicated by more regressions back to the target word and more total time spent on the target word, and the ultimate effect produced by increasing the number of lower frequency neighbors was a small and insignificant increase in the total time to read the sentence.

General Discussion

The present data have a number of implications for models of visual word recognition. Undoubtedly, the presence of an inhibitory effect of neighborhood size raises critical theoretical issues, the most important being the role played by competitive processes in word recognition. Keep in mind that a central claim of activation models is that word processing is based on a process of competition between simultaneously active candidates, with the selection decision being made as the node corresponding to the stimulus word emerges from among the rest of the candidates.

Experiment 1, using the lexical-decision task, showed a facilitative effect of neighborhood size (i.e., the total number of neighbors) when the frequency of the highest frequency neighbor was controlled. In contrast, Experiment 2, which embedded the same words in sentences, found an inhibitory effect of neighborhood size on reading. Moreover, there was no evidence for facilitation in any reading measure, indicating that if there was any facilitative effect produced by the neighborhood size manipulation, it was swamped by inhibition even in early stages of processing. In the stimuli of Experiments 1 and 2, however, the total number of neighbors was confounded with the number of higher frequency neighbors, and regression analyses in Experiment 2 indicated that the number of higher frequency neighbors played an inhibitory role and that the number of lower frequency neighbors may have played a weak, facilitative role. Experiment 3 varied the number of lower frequency neighbors, holding the number of higher frequency neighbors constant, and indicated that the number of lower frequency neighbors had what may have been a facilitative role in early processing, although it had an inhibitory effect later in processing.

The Neighborhood Size Effect in Reading

The fact that N had opposite effects on lexical decision and reading for the same words (in Experiments 1 and 2) is striking and puzzling. The reason we are puzzled is because in many current models of word identification, a larger neighborhood facilitates processing as a result of either (a) greater excitation in the lexicon because there are more lexical entries activated or (b) facilitation from the lexicon that feeds back to excite component letters. Such facilitation is thought to occur relatively early in processing, even in models without discrete processing stages. Because we were influenced by these theories, we expected to find facilitation effects in Experiment 2 early in processing, plausibly

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the highest frequency neighbor. The participants were asked to indicate whether the sentence fragment made sense or if it was anomalous. The sentence fragments that were classified as the highest frequency neighbor being a plausible continuation were rated as making sense 96% of the time (averaged over subjects and items), whereas those that were classified as the highest frequency neighbor being anomalous were classified as only making sense 2% of the time.

Table 5
Regression Slope Coefficients for Number of Higher Frequency Neighbors' (NHI) and Lower Frequency Neighbors' (NLO) Eye-Movement Indexes Compared Across Experiments

Eye-movement measure	Experiment and predictor: Perea & Pollatsek's (1998) Experiment 2 NHI	Perea & Pollatsek's (1998) Experiment 2 NLO	Experiment 2 NHI	Experiment 2 NLO	Experiment 3 NHI	Experiment 3 NLO
Probability of skipping target	0.6%	0.6%	−0.5%	0.6%	−4.6%†	−2.0%*
First-fixation duration	2 ms	−3 ms	4 ms†	−1 ms	9 ms*	0 ms
Gaze duration	4 ms	−3 ms	7 ms*	−1 ms	7 ms	−2 ms
Spillover	6 ms*	0 ms	3 ms†	−3 ms*	3 ms	−1 ms
Probability of regressing back to target	3.6%*	−0.2%	0.7%	0.0%	5.5%*	0.9%
Total time	19 ms*	−1 ms	10 ms*	−1 ms	32 ms*	9 ms†

Note. The other predictors in the multiple regression equations were the log of the frequency of the target word, the number of letters in the target word, the number of syllables in the target word, and the average positional bigram frequency of the target word.
†$p < .10$ (marginally significant). *$p < .05$.

followed by later inhibition effects. Instead, there was no hint of a facilitative effect for increasing neighborhood size in Experiment 2 at any stage in processing.

We return later to discuss these discrepancies between the lexical-decision and reading data. For the present, we concentrate on the reading data from Experiments 2 and 3, which are in fact reasonably consistent with the reading data of Perea and Pollatsek's (1998) Experiment 2 mentioned earlier, even though the variable that was explicitly varied differed among the three experiments. In Perea and Pollatsek's study, the experimental contrast was between words with at least one higher frequency neighbor and words with no higher frequency neighbor (holding N constant), whereas in Experiment 2 of our study, N was varied, with the higher N words having both more higher frequency neighbors and more lower frequency neighbors. The results of the two experiments were reasonably consistent: Both found consistent inhibitory effects in reading that were due to increasing the number of higher frequency neighbors. The inhibitory effects that were due to increasing the number of higher frequency neighbors in Perea and Pollatsek's study and the total number of neighbors in our Experiment 2 were, respectively, as follows: 0.5% and 2.3% for the probability of skipping, 4 ms and 11 ms for first-fixation duration, 2 ms and 24 ms for gaze duration, 12 ms and 2 ms for spillover, 6.6% and 4.5% for the probability of regressing back to the target word, and 23 ms and 51 ms for the total time on the target word. Thus, even though significant inhibition occurred earlier in our study than in theirs, the differences appear to be quantitative rather than qualitative: Inhibition that was due to having more high-frequency neighbors was stronger and earlier in Experiment 2 of our study.

In fact, because the manipulations in the two experiments were somewhat different, it is perhaps fairest to compare them using multiple regression analyses. Table 5 summarizes the results of the regression analyses presented earlier for Experiments 2 and 3 and for Perea and Pollatsek (1998), Experiment 2.[5] As seen in the table, the estimates for the effects of higher frequency and lower frequency neighbors are quite similar in all three experiments on all the measures up through spillover, except for the skipping effects in Experiment 3. The inhibitory measures on regressions and total time are bigger in Experiment 3 than in the other two experiments (as we argued earlier) because the readers were paying the price for misidentifying the target word when they skipped it.

A post hoc analysis of Perea and Pollatsek's (1998) Experiment 2 also indicated that the speed of the inhibitory effect may differ among participants. They divided the readers into two equal groups on the basis of the number of overall regressions that each reader made and found that there was a reliable 15-ms inhibition effect on gaze duration for the half of the readers who made fewer regressions and a small, unreliable, facilitation effect for the readers who made many regressions. A similar analysis of our Experiment 2 revealed an analogous pattern, with the readers who made few regressions showing a bigger inhibitory effect early in processing: For the readers with fewer regressions, the inhibitory effects in mean first-fixation duration and gaze duration were 14 ms and 28 ms, respectively, whereas for the readers with more regressions, the values were 7 ms and 19 ms, respectively. Thus, it appears that the speed at which inhibitory effects occur may differ across readers. This strengthens the hypothesis that difference between Experiment 2 in the two studies is merely quantitative: The inhibitory effect in the present study was bigger and became significant earlier for all readers.

To summarize, the data from Perea and Pollatsek's (1998) Experiment 2 and Experiment 2 of the present study indicate

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[5] The regression analysis we report here for Perea and Pollatsek (1998), Experiment 2, is the one in which all items (both those with higher frequency neighbors and those with no higher frequency neighbors) were used.

that increasing the number of higher frequency neighbors produces no facilitative effects in any reading measure and produces an inhibitory effect in which speed of activation appears to depend on the number of higher frequency neighbors that a word has and possibly on the type of reader. Moreover, in our Experiment 2, this inhibitory effect was sufficient to mask any possible facilitative effect of increasing the number of lower frequency neighbors.

Experiment 3, however, suggested that there may be facilitative effects early in processing that were due to having more lower frequency neighbors when the number of higher frequency neighbors was held constant. It is not clear, however, that the bulk of this effect, which was on the probability of skipping the target word, can really be considered "facilitation." That is, when the relation of the sentence context to the highest frequency neighbor was examined, it appeared that the increase in skipping was due to lower frequency neighbors increasing the probability that the target word was (at least tentatively) misidentified as its highest frequency neighbor. This interpretation is supported by the data that indicate that greater skipping probabilities were associated with greater regression probabilities and a consequent small increase in the total time spent in reading the sentence. Thus, the skipping data indicate that more lower frequency neighbors facilitate the encoding of something, but not necessarily the target word. There was, however, a suggestion of a facilitation effect on the gaze duration on the target word that was not plausibly due to such misidentification, as it occurred more strongly in those sentences in which the higher frequency neighbor was implausible with the sentence context.

The above discussion of the skipping data raises the question of how the higher frequency neighbors interfered with reading. At a global level, there appear to be two plausible alternatives, which are not mutually exclusive. One is that the target word, on a fraction of trials, was actually misidentified as a higher frequency neighbor and then, at some point, the reader realized from the sentence context that the word was probably misidentified and needed either to re-encode the visual information or to deduce what the misidentified word was likely to have been from the context. The second alternative is that the higher frequency neighbors were not actually identified but competed with the target word to slow down the identification process. This competition could be viewed either as occurring in terms of a discrete "candidate set," as in activation-verification models (e.g., Paap et al., 1982), or simply in terms of relative activation in the lexicon in terms of interactive-activation models. The subsidiary analysis of the skipping data in Experiment 3 indicated that the misidentification process occurred at least some of the time, but the gaze duration data in Experiment 2 indicated that the competition process also occurs in reading.

It is tempting to assume that these two processes can be broken down neatly with respect to the eye-movement measures in the following manner: The inhibitory effects that occur while fixating the target word (e.g., lengthened gaze durations) reflect the second mechanism (slowed lexical access), whereas inhibitory effects that occur after the target word has been fixated reflect the first mechanism (misidentification of the target word as a higher frequency neighbor). However, we think it is unlikely that the division is nearly that precise. A recent quantitative model of eye movements in reading (Reichle et al., 1998) indicates why. The model posits that the signal to leave a word (which is the primary determinant of gaze duration) is not completion of lexical access but only a partial stage of lexical processing, called a *familiarity check.* Such a division was necessary in the model to predict a variety of phenomena, most notably spillover effects. As a result, this model predicts that the time to complete lexical access is not only reflected in first-fixation durations and gaze durations but also in the duration of spillover fixations and even in some regressions back to the target word. The prediction about spillover effects is consistent with a large amount of data that indicate that effects that appear to be "lexical" (such as word-frequency manipulations) show up in spillover measures as well as in gaze duration on a target word; however, the prediction about regression effects is more speculative.

Thus, we think it is prudent not to assume that there is a clear dichotomy, with effects that occur on a target word (e.g., gaze durations) reflecting lexical processes and effects that occur afterwards (e.g., spillover, regressions) solely reflecting postlexical processes such as repairing misidentifications. The data on the effects of the number of higher frequency neighbors, in which inhibitory effects of higher frequency neighbors apparently migrate from gaze duration to later measures depending on the number of higher frequency neighbors or on the particular group of readers being analyzed, support the hypothesis that there is not a strict dichotomy between lexical and postlexical processes on the basis of whether they occur before, during, or after the target word has been fixated. Eye movements, though, are a valuable source of information on the time course of processing during reading. That is, effects that occur early (i.e., before or while the target word is fixated) are likely to be chiefly reflecting lexical processes, whereas later effects are likely to be reflecting postlexical processes as well.

We should briefly mention one earlier reading study that varied something similar to neighborhood size and obtained data apparently at variance with those of Experiment 2. Lima and Inhoff (1985) manipulated *constraint,* defined by the number of words that began with the first three letters of the target word (e.g., *clown* vs. *dwarf*), and found that words with less constraint had shorter first-fixation durations and shorter gaze durations than words with greater constraint. (Unfortunately, Lima and Inhoff did not report any data concerning the probability of skipping the target word, the percentage of regressions back to the target word, or the total time spent on the target word.) Although they did not explicitly vary neighborhood size, it is likely that the words with fewer cohorts in the first 3 letters, such as *dwarf,* also had fewer neighbors than words like *clown.* Thus, their finding could be interpreted as a facilitative effect on early processing that was due to a larger neighborhood. This is not the only possibility, however, as the difference between their conditions may be due to the low initial trigram frequency of the words with smaller neighborhoods. (In most neighborhood size studies, bigram and trigram frequency are controlled.) Therefore, these results are not necessarily inconsistent with ours.

The Neighborhood Size Effect and Models of Visual Word Recognition

We return now to attempt to reconcile our reading data with the lexical-decision data of Experiment 1 and those of studies in which facilitative effects of neighborhood size have generally been found. In Experiment 1, we found the usual facilitative effect of neighborhood size on lexical-decision times and error rates (see Andrews, 1989, 1992; Carreiras et al., 1997; Forster & Shen, 1996; Huntsman & Lima, 1996; Johnson & Pugh, 1994; Perea, 1993; Sears et al., 1995). If this effect is directly tapping lexical access, it could be used to undermine the assumption that competition between word units plays any significant role in lexical access (Forster & Shen, 1996). As Andrews (1997) pointed out, the dominance of this metaphor has been responsible for the continued reluctance of researchers to accept that facilitative effects of neighborhood size are due to lexical retrieval. However, as we said earlier, the lexical-decision task can, in principle, be performed without lexical access. There is little doubt that "word" responses can be made without a perfect match between sensory input and lexical representations (Andrews, 1996; Balota & Chumbley, 1984; Grainger & Jacobs, 1996; Paap & Johansen, 1994). Furthermore, there is the possibility that some proportion of participants' responses to target words are based on incorrect retrieval of their higher frequency neighbors (Andrews, 1996). As a result, the lexical-decision task may be an unreliable index of the impact of co-activation of similar lexical representations. Given the ambiguity of this task as a measure of lexical access, conclusions concerning the locus of the effect of neighborhood size require converging evidence from other tasks. The fact that the lexical-decision effects are contrary to reading—a more "ecological" task—suggests that one should be skeptical that the lexical-decision task is directly tapping the process of lexical access.

As we said earlier, an inhibitory effect of the number of (higher frequency) neighbors is predicted by search or verification models (the activation-verification model, Paap et al., 1982; the search model, Forster, 1976; but see Forster, 1989). In these models, the neighborhood is a list of items ordered from the most frequent to least frequent members. In the selection process, each member of the neighborhood is checked from the top of the list down until the correct item is located. This account of the selection process accurately predicts a cumulative effect of number of higher frequency neighbors such as that found in Experiment 2 or in the study of Perea and Pollatsek (1998). In addition, the latest version of the activation-verification model (Paap & Johansen, 1994) also accurately predicts the presence of a facilitative effect of increasing N in the lexical-decision task. The underlying assumption behind this prediction is that a significant proportion of lexical decisions are based on a global lexical-activation mechanism rather than on lexical access and that words from large neighborhoods benefit more from that mechanism than words from small neighborhoods.

The more popular parallel models (interactive-activation model, McClelland & Rumelhart, 1981; the multiple read-out model, Grainger & Jacobs, 1996) assume that the units corresponding to the more frequent words have higher resting levels than the units corresponding to less frequent words. 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. Because the predictions of these models are not transparent, simulations are needed to know what the models predict for the materials used in Experiments 1 and 2.

Simulations were run with a version of the interactive activation model that had previously predicted inhibition because of increasing neighborhood size (see Jacobs & Grainger, 1992). 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 (see Grainger & Jacobs, 1996, for a similar adjustment). In the simulation, word-identification latencies were determined by the number of cycles that it took until the activation at a word node reached a threshold of 0.70. In these simulations, the model failed to capture the inhibitory effect of neighborhood size obtained in the reading data of Experiment 2: An average of 20.1 processing cycles was needed for words with few neighbors, whereas an average of only 19.6 processing cycles was needed for words with many neighbors.

We are not sure why this version of the interactive-activation model, which had previously predicted inhibitory effects for increasing N with other materials, predicted weak facilitation effects with our materials. We suspect that a major reason was that all the target words in Experiments 1 and 2 had at least one higher frequency neighbor. The simulations seemed to indicate that a higher frequency neighbor was often more interfering in the case of words from small neighborhoods than in the case of the words with many neighbors because the higher frequency neighbors tended to "kill each other off." To disentangle the role of the higher and lower frequency neighbors in the interactive-activation model, we conducted regression analyses on the number of processing cycles per item. The correlation between the number of lower frequency neighbors and the number of processing cycles approached significance ($r = -.20, p = .08$), when we partialed out the effects of log of word frequency, number of higher frequency neighbors, number of letters, and number of syllables. In contrast, a similar analysis did not show any signs of a correlation between the number of higher frequency neighbors and the number of processing cycles ($r = .03$).

Therefore, the effects of this simulation looked like the lexical-decision data (see Experiment 1) rather than the reading data, with facilitation from a larger number of lower frequency neighbors (probably through reverberating activation from the letter level; see Andrews, 1992) and no cumulative effect of the number of higher frequency neighbors (as in the simulations reported by Grainger, 1990). The predictions of the multiple read-out model (Grainger & Jacobs, 1996) for reading would not differ from those of the interactive-activation model in an identification task, because the two new parameters that the model implemented are specific to modeling global lexical-activation effects in the lexical-decision task. As a result, the multiple read-out model would predict even stronger facilitation from increasing N than the above simulation as long as a proportion of the participants' responses was based on global lexical activation.

Thus, the presence of an inhibitory effect of the number of higher frequency neighbors in reading (see also Perea & Pollatsek, 1998) poses a problem for interactive-activation models. This problem may not be insoluble because, as we said earlier, variations in the set of parameters in those models (e.g., the inhibition among word nodes) can yield very dramatic changes in how orthographic neighbors affect performance. However, at present, it is not clear whether any set of parameters can be found that will successfully be able to model (simultaneously) the neighborhood size effects from a wide variety of experiments.

Summary

To summarize, the results of the present study indicate that higher frequency neighbors inhibit lexical access in reading. This inhibition can be conceptualized as a competition process among lexical entries (Experiment 2). Moreover, there were only hints of facilitation effects because of having more low-frequency neighbors than are predicted by some models of lexical access. Target words with more low-frequency neighbors were skipped more often (but this was likely due to their being misidentified as higher frequency neighbors), and facilitation effects on gaze durations and spillover durations were small and not reliable (Experiment 3). In addition, the fact that the effects of increasing N in the lexical-decision data (Experiment 1) were opposite to those in the reading data (Experiment 2), even though the same stimuli were used in the two experiments, casts doubts on the use of the lexical-decision task as a tool for assessing the effects of orthographic neighborhood.

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Appendix A

Sentences Used in Experiment 2

He knew that the [icon,wand] with magic properties played a big role in the fable.
John knew that the [axle,horn] in the car he just bought needed repair.
Last year a new [germ,worm] in the region proved to be a health hazard.
The family was upset by the [feud,spat] between the two brothers.
Each morning, he saw the same [wren,loon] fly by in front of his property.
Ann thought the new [sofa,lamp] would really improve the appearance of her living room.
Everyone knew the [ruin,raid] of the fortress was certain by tomorrow.
The little known [sect,clan] had many unusual rituals.
His choice of [verb,robe] seemed odd and inappropriate.
The hikers were surprised when a [frog,deer] jumped onto the path.
The evening concluded with his favorite [aria,tune] from the opera.
Minute by minute, Bill's [fury,lust] increased as he thought about the encounter.
Robert didn't expect any [pity,fame] after finishing fourth in an eight man race.
All Gene needed was a [plug,gear] in order to finish the repair job.
For the most part, [fish,rice] was the staple of the diet of the region.
The focus of the painting was a [serf,moat] in front of an old castle.
Linda particularly enjoyed the [surf,dune] at the beach near her cabin.
Without the [knob,hook], it would have been difficult to manage the equipment.
Jennifer expected that the [turf,moss] on her property would attract animals to graze.
As Laura expected, her new [gown,cape] was the talk of the dance.
The children laughed when the [otter,mouse] darted out from the tall grass.
In the back, the [fence,track] marked the side of the property.
The old [basin,stove] would have to be repaired before the cabin could be sold.
The sauce on their uncle's [beard,shirt] was amusing to the children.
Immediately afterward, [grief,shame] was Amy's strongest emotion when she lost the race.
It took time to figure out that a damaged [rotor,crank] was the source of the problem.
It was not surprising that the [giant,witch] in the movie was scary to the children.
Michael added a bit of [flour,spice] to the meat while he was browning it.
Sheila pulled the [shawl,quilt] over her to keep warm on the cold winter night.
Keith knew that the [frost,sleet] on the windshield would make driving hazardous.
It was generally agreed that the design of the [manor,tower] was ingenious.
Everyone wanted to see the baby [whale,shark] at the aquarium.
The large [trunk,plank] in the attic was difficult to move.
A gold [medal,crown] was the first prize at the national beauty contest.
John took the last [apple,peach] from the bowl and started to peel it.
Harry's unethical [pause,trick] disconcerted his opponent at the chess match.
Tom was worried that his [ankle,spine] wouldn't heal properly.
Today, the lamb [curry,patty] looked like the best thing on the menu.
Arthur was trying to cope with the [flood,stack] of mail delivered after his vacation.
In many ways the [liver,shell] is the most important organ of an oyster.

Note. The target words (also used in Experiment 1) are in brackets; the one with fewer neighbors is listed first.

(*Appendixes continue*)

Appendix B

Sentences Used in Experiment 3

The principal [fault,charm] of the new movie was that it had many flashbacks.
They were suddenly aware of an unpleasant [vapor,noise] coming from the next room.
When Bobby came home from school, he had some [juice,candy] before going out to play.
Because of the star's erratic behavior, his [agent,coach] became increasingly worried.
John picked up some [fruit,lunch] at the deli before going back to work.
Susie liked to use her [thumb,spoon] to mash her potatoes.
After the long hike, the [troop,squad] came back to their bunks exhausted.
He was having difficulty cutting a [notch,wedge] out of the block of wood.
Mary was pleased with the new [skirt,purse] she bought at the mall.
Ellen was struck by the [grief,folly] of the man who had gambled away his life savings.
Sam put his beer down on the [shelf,ledge] before answering the phone.
John had never noticed the [fence,bench] next to the statue before.
The pain in Robert's [ankle,belly] was becoming unbearable.
Everyone thought Tony's new [beard,shirt] looked good on him.
He didn't mind wading into the [flood,creek] as long as he was adequately protected.
Jeanette got quite chilled from being in the [storm,shade] for a half hour.
Sarah heard a [curse,click] coming from downstairs and quickly sat up in bed.
The ornate [manor,spire] dominated all the photographs of the little village.
The strange modern sculpture was made of [cloth,steel] and wood.
The needle penetrating his [nerve,spine] was starting to cause numbness.
It was strange that the actress's [knee,chin] was the focus of the publicity photos.
Karen wanted a new [gown,coat] for the big society ball that she was going to.
David wanted to get to the [ridge,crest] before resting for a few minutes.
The sudden [pulse,blast] of lightning scared everyone in the room.
They felt that George's [focus,skill] on the court was why he won.
When Jerry saw the [cargo,crane] on the dock, he knew there was work to be done.
When the grocer counted his change, the [thief,crook] took fifty dollars and ran.
He had to be careful because the [print,paste] was still wet on the paper.

Note. Target words are in brackets; the one word with fewer neighbors is listed first.

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