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Neighborhood Effects in Visual Word Recognition: Effects of Letter Delay and Nonword Context Difficulty

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The role of a target's orthographic neighborhood in visual word recognition was investigated in 2 lexical decision experiments. In both experiments, some stimuli had 1 letter delayed relative to the presentation of the rest of the stimulus. Experiment 1 showed that delaying a letter position, which yielded a potentially competitive neighbor, was more costly to target recognition than delaying a position that yielded no neighbors. This effect was strongest when one of these neighbors was of higher frequency than the target itself. Additionally, the effect was reduced for words with a high friendly-to-unfriendly-neighbor ratio (friendly neighbors being those words containing the delayed letter). In Experiment 2 the difficulty of the word–nonword discrimination was manipulated by varying the density of the nonwords' neighborhoods. Only when the nonwords had many neighbors at several positions did the word responses show neighborhood competition effects.

Recent investigations of visual word recognition suggest that a target word's orthographic neighbors play a role in the process of recognizing that target (Andrews, 1989, 1992; Grainger 1990, 1992; Grainger, O'Regan, Jacobs, & Segui, 1989; Johnson, 1992; Johnson & Pugh, in press; Pugh, Rexer, & Katz, 1994). An orthographic neighbor is usually defined as any same-length word that differs from the target by a single letter (e.g., Coltheart, Davelaar, Jonasson, & Besner, 1977). By such a definition, neighbors of the word *mill* include *pill*, *mall*, and *milk*. The commonly used N metric measures the size of a word's neighborhood; it is simply a count of a word's neighbors. Most major theoretical accounts of word recognition propose that words that share letters with a target word become activated during target recognition (Forster, 1976; McClelland & Rumelhart, 1981; Morton, 1969; Paap, McDonald, Schvaneveldt, & Noel, 1987).

The theoretical role that activated neighbors play in target recognition is a complex one; depending on the model and its specific architectural assumptions (see below), neighbors are predicted to have either a facilitatory or an inhibitory effect on a target word's recognition. The results of the several empirical investigations into neighborhood effects have been equivocal; evidence showing facilitatory, inhibitory, and null effects of neighborhood size has been reported (Andrews, 1989, 1992; Coltheart et al., 1977; Grainger, 1992; Johnson, 1992; Johnson & Pugh, in press).

Pugh et al. (1994) offered a rationale for the contradictory effects of neighborhood size, one based on strategic considerations. They proposed that when the subject is able to initiate a lexical decision on the basis of the early superficial activation of many neighbors (without knowing exactly which activated word is actually the target), then words with many neighbors will be at an advantage (e.g., Balota & Chumbley, 1984). In contrast, if the task requires the subject to initiate a decision only after the target word has been precisely discriminated from all other words in the lexicon, then words with many neighbors will be at a disadvantage. In line with Johnson and Pugh (in press), Pugh et al. also demonstrated that an index of neighborhood size they called *spread* (the number of letter positions in the target word that yield at least one neighbor) was a better predictor of neighborhood effects than was the conventional N metric originally proposed by Coltheart et al. (1977).

The current set of experiments was designed to do three things: (a) to provide further experimental evidence for the psychological reality of the concept of neighborhood activation, (b) to test the claim that letter positions yielding neighbors require greater processing than positions not yielding neighbors, and (c) to test Pugh et al.'s (1994) claim that the role that these activated neighbors play changes as a function of task-related strategic requirements. To introduce the issues, a brief description of two major classes of theories that predict somewhat different patterns of neighborhood effects follows, along with a review of relevant neighborhood investigations.

Models of Word Recognition

Two major classes of word recognition models are usually distinguished: search models and activation models (Forster, 1976, 1992; Gordon, 1983; McCann, Besner, & Davelaar, 1988; McClelland & Rumelhart, 1981; Morton, 1969; Paap et al., 1987; Rumelhart & McClelland, 1982; Seidenberg & McClelland, 1989).

Search models generally contain the assumption that a partial analysis of the stimulus is used to rapidly generate a set of lexical candidates. These are then examined in more detail, one at a time, until a match with the stimulus is made. Examples of this class include Forster's model (Forster, 1976)

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and the activation-verification model of Paap and his associates (Paap et al., 1987; Paap, Newsome, McDonald, & Schvaneveldt, 1982). In Forster's account, input to the master lexicon is achieved by way of modality-specific memories organized on both a frequency and similarity basis. When initial morphemic units in the word are encoded, a frequency-ordered search of elements in the memories is undertaken until a best match is made. In general, the larger the number of neighbors, the more likely it is that the target will not be the most frequent of its set of neighbors. Consequently, frequency-ordered search models predict that the more neighbors a target has, the longer, on average, the search process should take (Grainger, 1992).

In Paap et al.'s (1982) activation-verification model, it is assumed that the stimulus input activates letter units, and that these in turn activate (in parallel) the lexical entries that are most consistent with the letters. The entries in this candidate set are then compared one at a time with a representation of the stimulus, the order of search being based on word frequency. Both of these search models predict inhibitory effects of increasing neighborhood size if the increase in N is associated with an increase in the number of neighbors that are of higher frequency than the target.

Activation models, on the other hand, are capable of predicting effects of neighborhood size that are either facilitatory or inhibitory, depending on their architectural specifics. These models propose that each sublexical representation that is activated by the input sends activation to every lexical entry that is consistent with it. The actual target word, which best matches the input, will be the most strongly activated and thus become recognized. McClelland and Rumelhart have proposed an interactive-activation model that uses principles that are capable of accounting for neighborhood effects (McClelland & Rumelhart, 1981; Rumelhart & McClelland, 1982). An important activation mechanism for McClelland and Rumelhart's model is the top-down feedback from activated word representations to letter representations. Every word that shares letters with a target will become activated by those letters during the initial stage of recognition and, by means of feedback from the word level to the letter level, the letter recognition process will be facilitated. Despite this facilitation, the target word itself can be recognized more slowly as N increases because, within the word level itself, intraword inhibitory connections cause activated words to suppress one another. Thus, depending on the relative strengths of these various connections, the model can predict facilitatory, inhibitory, or even null effects of neighborhood size on recognition latencies. Because the strength of the weights on different kinds of connections are adjustable, the model can, in principle, be made to account for contrasting results.

Prior Research on Neighborhood Effects

In the spoken word recognition literature, inhibitory effects of neighborhood size have been reported (Goldinger, Luce, & Pisoni, 1989; Luce, 1986; Pisoni, Nusbaum, Luce, & Slowiaczek, 1985). In the printed word recognition literature, on the other hand, contradictory neighborhood effects have been found. In a seminal investigation, Havens and Foote (1963) found that under tachistiscopic viewing, words from dense neighborhoods were harder to detect than words from sparse neighborhoods. However, Luce (1986) obtained the opposite pattern of results using similar procedures. Johnston (1978) found no evidence that the probability of letter detection was influenced by neighborhood size. Coltheart et al. (1977) manipulated the number of neighbors (*N*) in a lexical decision task and found no influence on word recognition latencies, although for nonwords, responses to large-*N* stimuli were slower and more prone to error than responses to small-*N* stimuli. Grainger and his colleagues (Grainger, 1990; Grainger et al., 1989) also found no influence of *N* on word latencies, but did find that words with at least one higher frequency neighbor were responded to more slowly than words without higher frequency neighbors.

Andrews (1989, 1992) challenged these null neighborhood-size results by crossing *N* with frequency in several lexical decision and naming studies. Even when controlling for bigram frequency, Andrews (1992), found that large-*N*, low-frequency words were responded to more quickly than small-*N*, low-frequency words; no effects of *N* were evident for high-frequency items. Like Coltheart et al. (1977), Andrews found that large neighborhoods slowed nonword rejection latencies.

Further complications come from several lexical decision experiments reported by Johnson and Pugh (in press). In an initial set of experiments in which words and nonwords were blocked by *N* (large or small *N* words and nonwords co-occurred within the same block), they found, in contrast with Andrews (1992), that both large-*N* words and nonwords were responded to more slowly than small-*N* items. They also concluded after further experimentation that the number of letter positions in the target word yielding at least one neighbor (*P*, or in our terms, spread) had a greater influence on latencies than did *N*. In their Experiment 6, Johnson and Pugh showed that words and nonwords were blocked by small versus large *P* (with *N* controlled for), and they found increased latencies for large-*P* words and nonwords. However, when they manipulated *N* while controlling for *P*, a small latency advantage for large-*N* words over small-*N* words was obtained.

Recently, Pugh et al. (1994) used a regression design to examine the effects of neighborhood distribution. They contrasted *P* (the number of letter positions yielding at least one neighbor), which they termed *spread,* and *N*, which becomes equivalent to depth (average number of neighbors at positions yielding neighbors) when *P* is included in the model. In an initial lexical decision experiment, Pugh et al. found that only spread was reliably related to latency and response accuracy. Spread had a facilitatory influence on word latencies (as spread increased, response time decreased) while it inhibited nonword rejection latencies and accuracy. This facilitatory influence of spread on word latencies contradicts the inhibitory influence observed in Johnson and Pugh's (in press) experiments.

Pugh et al. (1994) hypothesized that the facilitatory influence of spread on word latencies observed in their experiment might be attributable, in part, to a response bias operating in lexical decision. Specifically, some subjects might tend to respond positively to items with larger spread values (their accuracy results supported this conjecture). (Note that Johnson and Pugh's, in press, blocking paradigm would have eliminated this bias because within a block, words and nonwords were uniform with respect to neighborhood values.) Consistent with this hypothesis, in Pugh et al.'s second experiment a facilitatory influence of spread on word latencies was found only when the words were presented along with sparse neighborhood nonwords (nonwords with low *N* and *P*). In this condition, spread was correlated with the letter string's lexical status (i.e., if spread was large, then the item was a word). This facilitatory influence was eliminated in the dense (high *N* and *P*) nonword context, where larger spread values were not indicative of lexical status. Evidence for the claim that subjects processed targets more carefully as nonword neighborhood depth and that spread increased came from the significant polysemy effect (decreased latency with increased number of meanings for word targets) that was observed only in the dense-neighborhood nonword condition. Finally, in Pugh et al.'s semantic access experiment (Experiment 3), in which subjects had to respond on contacting a word's meaning, spread had an inhibitory influence on response latency. In this task, no word–nonword discrimination was made, and response biases should have been eliminated.

An additional finding in Pugh et al.'s (1994) experiments indicated that the spread of higher frequency neighbors, rather than simple spread, may be a better index of neighborhood competition effects. For each word, the number of letter positions yielding at least one higher frequency neighbor was determined, and words were partitioned into those with narrow higher frequency spread (two or fewer positions yielding higher frequency neighbors) or wide higher frequency spread (three or more positions). This variable was significantly related to latencies in the dense-neighborhood nonword condition of their second lexical decision experiment and was also significant in their semantic access experiment. Words yielding higher frequency neighbors at several letter positions were responded to more slowly than words with narrow higher frequency spread. This inhibitory effect of higher frequency spread was obtained with the influence of total number of higher frequency neighbors statistically controlled for; therefore, the effect was not simply due to the number of higher frequency neighbors but rather to their spread across letter positions.

In the first experiment of the current study, we sought to verify the idea that letter positions yielding neighbors are processed differently than letter positions yielding no neighbors. Given the inhibitory influence of spread reported in several experiments, we proposed that a letter position yielding at least one neighbor, particularly a higher frequency one, will require more processing than a letter position that does not yield a neighbor, and that more processing translates experimentally into longer latencies. To obtain a relative measure of the processing differences between ambiguous and unambiguous letter positions, we used a letter-delay manipulation. By delaying the onset of a letter, we sought to amplify the influence of that position's neighbors. The relative cost of letter delay should be greater when the letter delayed is ambiguous (yields neighbors) than when it is unambiguous (does not yield neighbors).

In a second experiment, we examined the issue of whether subjects can adapt their response strategies as nonword context becomes more or less difficult. Specifically, we hypothesized that there would be a smaller difference in latencies between the ambiguous and unambiguous letter delay conditions when subjects viewed these words along with sparse neighborhood nonwords. However, when dense neighborhood nonwords are used, which we suggest forces the subject to completely discriminate the target from its neighbors, then a larger ambiguity effect should be found. Results of this type would not only demonstrate neighborhood competition effects but would provide clear evidence that subjects are remarkably flexible with regard to the type of information they use in making word–nonword discriminations (Balota, & Chumbley, 1984, 1985; Gordon, 1983).

Experiment 1

We examined the dynamics of neighborhood competition by using a letter-delay paradigm. Four-letter word and nonword stimuli were presented in a lexical decision task. For each of the word stimuli, one of the medial letter positions yielded at least one neighbor, whereas the other medial position yielded no neighbors (henceforth called the ambiguous and unambiguous letter positions, respectively). Each word was presented in three different stimulus contexts: no delay, ambiguous letter position delay, and unambiguous letter position delay. Thus, each stimulus word served as its own control. The simple predictions were that letter delay, in general, would slow response latencies and, according to Pugh et al. (1994), that the effect of delaying an ambiguous letter would be more costly to latencies than delaying an unambiguous letter.

Method

Subjects. Thirty-nine undergraduate students from the University of Connecticut participated in this experiment for partial fulfillment of a course requirement.

Stimuli. One hundred four-letter words were selected. Word frequency ranged from 0 to 2,230 occurrences in Kucera and Francis's (1967) corpus. Each word yielded at least one neighbor at either the second letter position (46 words) or the third letter position (54 words), but not at both. The words' total number of neighbors and the extent to which their first and last positions yielded neighbors varied from word to word. One hundred pronounceable nonwords were generated; they varied on both the *N* and *P* dimensions (the number of orthographically defined neighbors and the number of letter positions yielding at least one neighbor, respectively).

Procedure. A standard lexical-decision procedure was followed. Each subject viewed the stimuli in uppercase letters on a Macintosh 512K computer screen in a different random order. Stimuli were preceded by, in succession, a 400-ms fixation point (an asterisk) and a 100-ms blank screen. Stimuli remained on the screen until the subject responded or until 1,500 ms had elapsed. The intertrial interval was 1,000 ms. Approximately one third of the stimuli were presented with all of their letters appearing on the screen simultaneously. A second third of the stimuli were presented with their second letters delayed by 100 ms relative to the presentation of the rest of the letters. (The first, third, and fourth letters were on the screen for five ticks of the computer's internal clock, 83 ms, followed by a clear screen interval, 17 ms, before the presentation of the complete stimulus pattern.) The remaining third of the stimuli were presented with their third letters similarly delayed. The delay of letters was distributed across stimuli such that an equal number of subjects viewed each word in each of the three delay conditions. Although a single subject viewed each stimulus only once, the delay of letters was also distributed across stimuli such that each subject viewed an approximately equal number of word stimuli with their neighbor-yielding letter delayed as with their non-neighbor-yielding letter delayed. Approximately one third of the nonwords were randomly chosen to have their second letters similarly delayed, and a second third of the nonwords were randomly chosen to have their third letters delayed. The remaining third of the nonwords were presented with all of their letters appearing simultaneously. The lexical status of 56% of the delayed-letter nonword trials could not be determined without resolving the delayed letter.

Subjects received standard lexical decision instructions and 40 practice trials. Subjects made "word" responses with their dominant hand and "nonword" responses with their nondominant hand on two telegraph keys. Response latency was measured from the onset of the initial letters in the target stimulus (either three or all four letters, depending on the condition).

Results

For each subject, mean word response latencies were calculated for each of the three conditions: no delay, delay ambiguous, and delay unambiguous. Trials with latencies greater than two standard deviations from the subject's mean (calculated independently for each condition) were treated as errors. Six subjects made more than 20% errors and were discarded from the analyses. For each subject, the percentage of correct word responses was also calculated for each condition. Three mean latencies were computed for each item, one for each of the delay conditions, averaging over only subjects' correct response times. The percentage of subjects who responded correctly to each item was also calculated separately for each of the three conditions. A reexamination of the stimuli revealed that one of the stimuli appeared twice and that two of the words did not have a neighborless medial letter. These words, plus two additional words (*CYST* and *GORE*) that more than 80% of the subjects failed to recognize as words, were eliminated from the analyses.

Analyses of variance (ANOVAs) were conducted on latency and accuracy data with both subjects (F_1) and items (F_2) as random factors. Initial analyses of the word-latency data were conducted to compare the no-delay condition with the average of the two delay conditions. These analyses revealed a large effect of letter delay, $F_1(1, 32) = 164.76, p < .001, MS_e = 412.46$, and $F_2(1, 93) = 150.68, p < .001, MS_e = 1{,}372.53$. The letter-delay manipulation slowed the processing of word targets; the no-delay condition's mean latency was 542 ms and the delayed condition's mean latency was 608 ms. An analysis comparing the ambiguous and unambiguous delay conditions revealed a significant effect of ambiguity, $F_1(1, 32) = 6.38, p < .02, MS_e = 526.76$, and $F_2(1, 93) = 7.79, p < .01, MS_e = 2{,}102.36$ (ambiguous = 618 ms; unambiguous = 599 ms). The differences between these means and the mean of the undelayed condition were 76 ms and 57 ms for the ambiguous and unambiguous delay conditions, respectively (the 19-ms difference between these differences is henceforth referred to as the *ambiguity effect*). Thus, delaying a letter that was at a neighbor-yielding position was more costly than delaying a letter that was at a position that yielded no neighbors.

The letter-delay manipulation did not reliably affect the accuracy of subjects' word responses, nor was there a reliable difference between the ambiguous and unambiguous letter-delay conditions, either by subjects or by items (all $ps > .05$; undelayed mean, 87% correct; ambiguous, 85%; unambiguous, 87%).

For nonwords, the presence or absence of a neighbor at delayed positions was not systematically manipulated. However, a comparison of the undelayed with the delayed conditions revealed a significant effect of delay on latency, $F_1(1, 32) = 29.41, p < .0001, MS_e = 402.09$, and $F_2(1, 98) = 8.33, p < .01, MS_e = 1{,}951.03$, (mean delayed = 653 ms; mean undelayed = 626 ms). The effect of letter delay on nonword response accuracy was significant by subjects, $F_1(1, 32) = 11.89, p < .01, MS_e = 15.66$, but not by items ($p > .15$). Subjects' nonword responses were more accurate in the delayed than in the undelayed condition, 91% and 88% correct, respectively.

Although items were not initially chosen with the relative frequency of the target and the neighbors at the ambiguous letter position in mind, an examination of the items indicated that 42 yielded at least one higher frequency neighbor at the ambiguous position, whereas for the other 52 words the neighbors yielded at the ambiguous position were of lower frequency than the target. To examine whether this stimulus characteristic had an impact on performance, we conducted an ANOVA on items with ambiguity as a repeated measure and relative neighbor frequency as a between-items variable. This analysis revealed a significant effect of ambiguity (as in the analyses on latency) and a significant ambiguity by relative frequency interaction, $F(1, 92) = 5.26, p < .05, MS_e = 2{,}010.31$. (The mean undelayed latencies were 533 ms and 553 ms for words in which the ambiguous position did not yield or did yield a higher frequency neighbor, respectively.) For words not yielding a higher frequency neighbor, the mean latency for the unambiguous delay condition was 599 ms, whereas the mean latency for the ambiguous delay condition was 604 ms. For words yielding at least one higher frequency neighbor, the means were 599 ms and 635 ms for the unambiguous and ambiguous delay conditions, respectively. Thus, as shown in Figure 1, there was only a 5-ms ambiguity effect when the ambiguous letter position yielded lower frequency neighbors but a 36-ms ambiguity effect when that letter position yielded at least one neighbor that was of higher frequency than the target. On the possibility that this result was an artifact of word frequency (words with higher frequency neighbors were, on average, lower in frequency than the words with no higher frequency neighbors), we included word frequency (log transformed) as a covariate. Frequency did not interact with ambiguity, and the relative neighbor Frequency × Ambiguity interaction was still significant, $F(1, 91) = 4.86, p < .05, MS_e = 2{,}032.41$. In short, this effect can be attributed to the frequency relation between the target and the neighbors at the delayed position. No significant effects were obtained in the corresponding accuracy analysis (group means ranged from 84% to 88% correct).

In the interactive-activation model of McClelland and Rumelhart (1981), activated lexical entries have top-down excitatory connections to letters with which they are consistent. A testable implication of this architecture is that as the ratio of the number of neighbors that contain the ambiguous

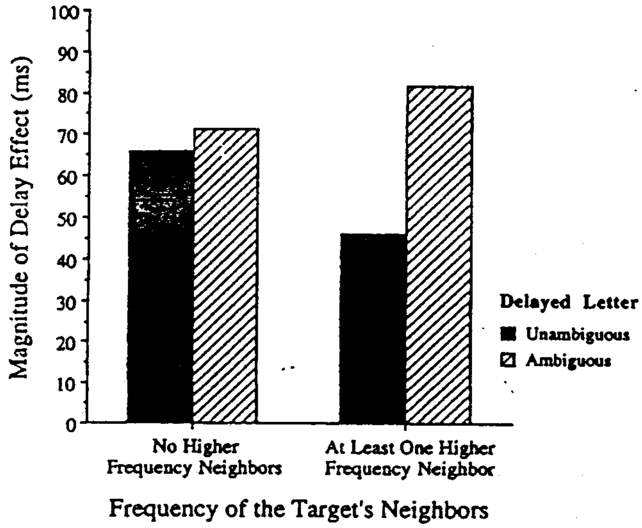

Figure 1. The delay effect in Experiment 1 as a function of the ambiguity of the delayed letter and the frequency of the target's neighbors.

letter (“friendly” neighbors) to the number of neighbors derived from the ambiguous letter position (“unfriendly” neighbors, which do not contain the delayed letter) increases, the ambiguity effect should diminish. That is, the more activated words that contain the delayed ambiguous letter (in this case neighbors from the first and last letter positions), the less costly the delay should be because presumably somewhat less bottom-up activation is required to bring the relevant letter detector to threshold. We divided our words into those with low friendly-to-unfriendly ratios (<3.5) and those with high friendly-to-unfriendly ratios (>3.5). This cutoff was used because it divided the words fairly evenly; there were 51 low-ratio words and 43 high-ratio words. The ambiguity by neighborhood friendliness interaction was significant, $F(1, 92) = 4.93, p < .05, MS_e = 2{,}017.23$. (For undelayed presentation the mean latencies were 546 ms and 538 ms for the low- and high-ratio words, respectively.) For the low-ratio words, the mean latency in the unambiguous delay condition was 603 ms, whereas in the ambiguous delay condition the mean latency was 635 ms. For words with a high ratio of friendly to unfriendly neighbors, the means were 595 ms and 598 ms for the unambiguous and ambiguous conditions, respectively. Thus, there was a 32-ms ambiguity effect for items with low friendly-to-unfriendly ratios but only a 3-ms effect for those with high ratios. This result suggests that the ambiguity effect can be offset to some extent when there are many neighbors that actually contain the ambiguous delayed letter.[1] Results from the corresponding accuracy analysis revealed no significant effects (group means ranged from 83% to 89% correct).

Discussion

The results from this experiment show quite clearly that delaying a letter position that yields a potentially competitive neighbor, even though this delay is quite brief, is more costly to target recognition latency than delaying a letter position that yields no neighbor. This converges with other studies to suggest a potentially competitive role in target recognition for words that are similar to that target. Furthermore, this neighbor competition effect was qualified by the frequency relation of the target to these neighbors. The ambiguity effect was considerably stronger for words that yielded higher frequency neighbors at the delayed ambiguous position than for words that were of higher frequency than these neighbors. This supports Grainger's claim (Grainger, 1990, 1992; Grainger et al., 1989) that the relative frequency of the target to its neighbors largely determines whether competition effects will emerge. These results are also consistent with the claims of Pugh et al. (1994) and Johnson and Pugh (in press) that the spread (the number of letter positions yielding neighbors), and particularly the higher frequency spread, is an important component of neighborhood effects. The results are also consistent with Pugh et al.'s and Johnson and Pugh's suggestion that letter positions yielding neighbors require a greater degree of processing than positions yielding no neighbors. That ambiguous letter positions require increased processing is suggested by the relative cost of delaying perceptual information for these letters compared with the unambiguous ones. Finally, it also appears that ambiguity effects might be offset, to a certain extent, when the ratio of friendly to unfriendly neighbors is high. This last result falls naturally out of the architectural assumptions of the interactive-activation model (McClelland & Rumelhart, 1981).

A final point about the technique: It is highly unlikely that subjects engaged in any sort of strategic guessing about the word before the final letter was printed. During informal subject debriefings, most subjects reported that they did not notice anything unusual about the presentation of the stimuli. Of those few who did, none described the manipulation (that one medial letter printed to screen later than the other three letters). With such a brief delay and without subjects' conscious awareness of it, it is unlikely that any postlexical guessing effects were operating in this experiment.

Experiment 2

Experiment 2 was conducted to determine whether the apparent neighbor competition observed in the first experiment would be eliminated under conditions that encouraged subjects to initiate lexical decisions before the resolution of neighborhood uncertainty. Balota and Chumbley (1984) suggested that under certain conditions, subjects can make lexical decision responses at a point before the target has been fully discriminated from its competitors. Pugh et al. (1994) found that in a context of uniformly sparse neighborhood nonwords (nonwords with few neighbors at few letter positions), words with high spread values were responded to more quickly than were words with low spread values. However, in a context of uniformly dense neighborhood nonwords (nonwords with many neighbors at many letter positions), the spread's facili-

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[1] It should be noted that when the number of neighbors at the ambiguous position is high, the friendly-to-unfriendly ratio tends to be low. Consequently, this factor alone might be responsible for the effect we obtained. To test this possibility we examined the effect of the number of unfriendly neighbors alone and found that this factor was not reliably related to response latency.

tatory effect on word response latency disappeared; an inhibitory influence of higher frequency spread on word latencies was observed. This suggests that only subjects in the sparse-neighborhood nonword condition were using spread as a positive response cue, that is, reading responses before neighborhood resolution. Such remarkable flexibility, demonstrated in response to such subtle nonword variations, speaks of fine attentional control over word recognition processes, and such control is probably not irrelevant to reading.

In the current experiment, as in Experiment 1, the delay of ambiguous versus unambiguous letter positions was contrasted. This experiment additionally manipulated nonword context: Subjects received either sparse-neighborhood nonwords or dense-neighborhood nonwords. If subjects can modulate lexical decision performance in the way we have suggested, then an ambiguity effect is expected only when the nonwords consist of uniformly dense-neighborhood items, items that encourage a more careful decision criterion. As in the first experiment, the interactions with relative neighbor frequency and the ratio of friendly to unfriendly neighbors were also examined.

Method

Subjects. One hundred and six undergraduate students from the University of Connecticut participated in the experiment in partial fulfillment of a course requirement.

Stimuli. The same 100 words from Experiment 1 were used, with the exception that 4 of the previously problematic items were replaced. Two lists of 100 nonwords were constructed according to the following criteria: All sparse items had $N \leq 2$ and $P \leq 1$ (e.g., KARG), and dense items had $N \geq 6$ and $P \geq 3$ (e.g., MAND). All subjects received the same set of words but only one of the two nonword contexts.

Procedure. The procedures were the same as those used in Experiment 1. The lexical status of 11% of the delayed letter, sparse-neighborhood nonword trials and 88% of the dense-neighborhood nonword trials could not be determined without resolving the delayed letter.

Results

The data were prepared for analysis as in Experiment 1. Again, a 20% error cut-off was used, and 10 subjects were excluded from the analyses on this basis. Two words, which more than 80% of the subjects failed to recognize as words, were eliminated from the analyses.

The initial analyses of word latencies revealed that the delayed trials (averaged across ambiguous and unambiguous conditions) were significantly slower than the undelayed trials, $F_1(1, 94) = 365.11, p < .001, MS_e = 483.74$, and $F_2(1, 97) = 515.14, p < .001, MS_e = 778.48$ (delayed trials = 582 ms, undelayed trials = 521). A significant nonword context effect was also obtained, $F_1(1, 94) = 8.21, p < .01, MS_e = 5{,}127.863$, and $F_2(1, 97) = 67.76, p < .001, MS_e = 729.81$. Word response latencies were slower in the dense-neighborhood nonword context (566 ms) than in the sparse-neighborhood nonword context (537 ms). The interaction between these two variables was not significant. In the corresponding accuracy analyses, delay was significant, $F_1(1, 94) = 40.24, p < .001, MS_e = 11.94$, and $F_2(1, 97) = 16.38, p < .001, MS_e = 62.68$. The delayed condition yielded 87% correct responses, whereas the undelayed condition yielded 90% correct. There was also a significant effect of nonword context on accuracy, $F_1(1, 94) = 9.28$, $p < .01, MS_e = 20.55$, and $F_2(1, 97) = 6.03, p < .02, MS_e = 66.61$. Subjects receiving the sparse-neighborhood nonword context made more correct word responses than subjects receiving the dense context (89% and 87% correct, respectively). The interaction between these two factors again was not significant (both $ps > .20$; group means ranged from 86% to 91% correct).

In the analyses of the two delay conditions, nonword context (sparse vs. dense) was a between-subjects variable and ambiguity (ambiguous vs. unambiguous letter position delay) was a repeated measure by subjects, and both were repeated measures by items. The effect of ambiguity was significant, $F_1(1, 94) = 13.21, p < .001, MS_e = 324.05$, and $F_2(1, 97) = 5.51, p < .05$ $MS_e = 1{,}622.04$, (ambiguous delay condition = 586 ms, unambiguous delay condition = 577 ms). The Ambiguity × Nonword Context interaction was also significant by subjects, $F_1(1, 94) = 6.55, p < .02, MS_e = 324.05$, but not by items ($p > .10$). For the sparse neighborhood condition, the mean latency was 565 ms for the unambiguous delay condition and 568 ms for the ambiguous delay condition. However, in the dense condition the corresponding mean latencies were 589 ms and 605 ms. Thus, the data revealed only a 3-ms ambiguity effect in the sparse nonword condition but a 16-ms ambiguity effect in the dense nonword context. Post hoc tests indicated that the 16-ms effect in the dense condition was significant both by subjects, $F_1(1, 47) = 17.48, p < .001, MS_e = 355.58$, and by items, $F_2(1, 97) = 7.84, p < .01, MS_e = 1{,}240.63$. The 3-ms sparse-condition ambiguity effect was not reliable in either analysis ($Fs < 1.0$). Response accuracy was not reliably influenced by the ambiguity of the delayed letter or its interaction with nonword context (group means ranged from 86% to 88% correct).

An analysis of the nonword data examined nonword context as a between-subjects factor and letter delay (delayed vs. undelayed) as a repeated measure in the subjects analysis, and both as between-items factors in the item analysis (different nonwords were used in the two contexts). The latency analysis revealed significant effects of nonword context both by subjects, $F(1, 94) = 18.13, p < .001, MS_e = 7{,}486.63$, and by items, $F(1, 196) = 89.36, p < .001, MS_e = 1{,}406.01$. The mean nonword response latencies for the sparse and dense conditions were 583 ms and 636 ms, respectively. Letter delay was also significant, $F_1(1, 94) = 223.48, p < .0001, MS_e = 305.32$, and $F_2(1, 196) = 45.00, p < .0001, MS_e = 1{,}406.01$. The mean nonword latencies for the delayed and undelayed conditions were 628 ms and 591 ms, respectively. The interaction between delay and nonword context was not significant (both $Fs < 1.0$).

The nonword accuracy analysis revealed significant effects of nonword context in the subjects' analysis, $F_1(1, 94) = 5.50$, $p < .05, MS_e = 23.75$. Subjects' responses to the sparse-neighborhood nonwords were more accurate (sparse = 91%, dense = 90%). Letter delay was also significant in the subjects' analysis, $F_1(1, 94) = 15.46, p < .001, MS_e = 10.32$. The mean percentage correct was 92 for the delayed stimuli and 90 for the undelayed stimuli. These effects were not significant in the items analysis (both $ps > .20$). The interaction between delay and nonword context was not significant (both subject and item *Fs* < 1.0).

Additional analyses. As in Experiment 1, the effects of the relative frequency of the target to its neighbors, as well as the ratio of friendly to unfriendly neighbors at the ambiguous letter position were examined. These item analyses involved nonword context and ambiguity as repeated measures and either relative neighbor frequency or friendly–unfriendly ratio as between-items factors.

In the relative neighbor frequency latency analysis, neither the relative neighbor frequency by ambiguity interaction nor the relative neighbor frequency by nonword context interaction was significant. (This is discussed later when the results of a combined analysis of both experiments are reported). Similarly, the ratio of friendly to unfriendly neighbors failed to interact with either nonword context or ambiguity. Accuracy analyses also failed to reveal significant effects, with the exception of a somewhat complex three-way interaction between relative neighbor frequency, nonword context, and ambiguity, $F(1, 96) = 4.29$, $p < .05$, $MS_e = 61.83$. An examination of the individual cells showed that although performance in the sparse condition was generally better than in the dense condition, this pattern was reversed on ambiguous delay items with at least one higher frequency neighbor.

Combined analysis of Experiments 1 and 2. Largely the same words were used in both experiments (96 of 100 were common to both), with the primary difference between the experiments being the characteristics of their nonwords. The data from these two experiments were examined together in overall ANOVAs. Recall that in Experiment 1, nonwords were not chosen with neighborhood density in mind and had a good deal of range on this dimension; we hereinafter refer to this as the mixed density nonword context. The two conditions in Experiment 2 had uniformly sparse or dense nonword contexts. This gives us three levels of nonword context for these analyses: sparse, mixed, and dense.

The overall Nonword Context × Ambiguity interaction was significant by subjects, $F_1(2, 126) = 3.21, p < .05, MS_e = 375.53$ (see Figure 2) but not by items ($p > .10$). The 3-ms effect obtained in the sparse context differed from the 19-ms and 16-ms ambiguity effects obtained in the mixed and dense contexts, respectively. The accuracy analyses yielded no reliable effects ($p > .10$ for the nonword context effect in the item analysis; all other subject and item *Fs* < 1.0).

A significant Nonword Context × Ambiguity × Relative Neighbor Frequency interaction was obtained in the combined item-based analysis, $F(2, 184) = 3.20, p < .05, MS_e = 964.91$. In the sparse-neighborhood nonword condition, neither the main effect of ambiguity ($p > .25$) nor its interaction with relative neighbor frequency ($p > .07$) was significant. The mixed condition, as discussed in Experiment 1, revealed a significant ambiguity effect and a significant interaction between ambiguity and relative neighbor frequency (see Figure 1). Finally, in the dense nonword context, although there was a significant ambiguity effect, $F(1, 92) = 6.26, p < .02, MS_e = 1{,}293.43$, its interaction with relative neighbor frequency was not significant ($F < 1$). Thus, although ambiguity effects were present in the two more difficult nonword contexts, in the uniformly dense condition, ambiguity effects were of similar magnitude regardless of whether the ambiguous position yielded a higher frequency neighbor. Response accuracy was not significantly influenced by relative neighbor frequency or any of its interactions ($p > .10$ for the triple interaction; $p > .20$ for all other effects).

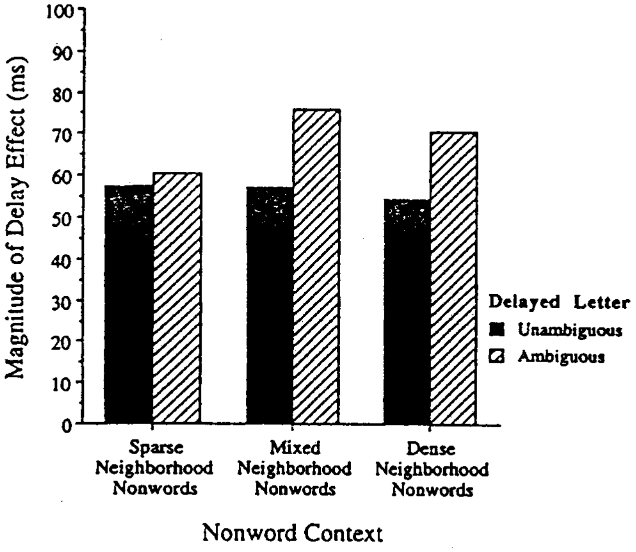

Figure 2. The delay effect in Experiment 2 as a function of the ambiguity of the delayed letter and the density of the accompanying nonwords' neighborhoods.

The analysis examining the ratio of friendly to unfriendly neighbors revealed a significant interaction between ambiguity and the friendly-to-unfriendly ratio, $F(1, 92) = 4.64, p < .05$, $MS_e = 2{,}686.22$. The ambiguity effect was considerably smaller in magnitude when the ratio of friendly to unfriendly neighbors was large (2 ms) than when it was small (21 ms). That suggests lexical constraint on positional ambiguity effects. No other interactions were reliable (all *ps* > .10); hence, the general constraint imposed by high friendly-to-unfriendly ratios (discussed in Experiment 1) was not qualified by nonword context. (Note however that the interaction between ambiguity and the friendly–unfriendly ratio did not obtain significance in the separate analysis of Experiment 2.) No significant effects were obtained in the corresponding accuracy analysis (all *Fs* < 1.0).

Discussion

In Experiment 2, once again delaying a letter position that yielded neighbors was more costly to latencies than delaying a position that yielded no neighbors. However, this effect was qualified by nonword context. When nonwords had uniformly low *N* and *P* values, there was essentially no difference between delaying positions yielding neighbors and delaying those that did not. However, in the more difficult high-*N* and high-*P* (dense) nonword context, an ambiguity effect was obtained. Apparently, subjects modulate their response criteria when the difficulty of the word–nonword discrimination changes. Furthermore, the combined analysis revealed that in both the mixed (Experiment 1) and dense conditions ambiguity was costly to latencies, and these conditions contrast with the sparse context.

The combined analysis examining relative neighbor frequency also revealed that the interaction between relative neighbor frequency and ambiguity obtained in the mixed context of Experiment 1 (wherein ambiguity effects were much larger for words yielding at least one higher frequency neighbor at the delayed position than for those words yielding lower frequency neighbors) was not present when nonwords were uniformly dense. In that dense condition, ambiguity, although reliable as a main effect, was no more costly for that subset of words yielding at least one higher frequency neighbor than for those that did not. This might be interpreted to indicate that in a context where nonwords are wordlike (presumably a difficult context), the presence of any neighbor at the delayed position is sufficient to delay responding. By contrast, when the nonword context is of intermediate difficulty, then only higher frequency neighbors are relevant competitors. Finally, when nonwords are uniformly easy (sparse condition), neighbor competition does not appear to influence subjects' responses.

However, there are problems with this interpretation of the relative frequency by ambiguity differences across conditions. First, it should be noted that the absolute magnitude of the ambiguity effect in the dense condition for words yielding at least one higher frequency neighbor at the delayed position was only 12 ms, whereas in the mixed context that same effect was considerably larger (35 ms). Why subjects in the mixed condition should have shown a larger ambiguity effect on these items than subjects in the dense condition is unclear. Perhaps other factors, such as a generally more conservative responding strategy, attenuated the absolute difference between the delay- and no-delay conditions in the dense nonword context. In any event, both the mixed and dense neighborhood nonword contexts clearly revealed effects that were due to positional ambiguity, and these effects were eliminated when uniformly sparse nonwords were used.

The interaction between ambiguity and the ratio of friendly to unfriendly neighbors was reliable in the combined analysis. This suggests that ambiguity effects can be offset to some extent as the number of neighbors containing the delayed letter increases (relative to the number of neighbors at this position).

General Discussion

Experiments 1 and 2 revealed that letter positions that yield neighbors are more adversely affected by onset delays than letter positions that do not yield neighbors. This result suggests, rather directly, that neighborhood competition effects are due, at least in part, to the additional processing of letter information required to resolve the neighbor-yielding letter positions. However, in the lexical-decision task, this ambiguity effect appears to be modulated to some extent by the characteristics of the nonword stimuli. When the nonwords consisted of items with uniformly sparse neighborhoods (i.e., the nonwords were not similar to many words) there was no evidence of an ambiguity effect. Presumably, it was relatively easy to make a word–nonword decision even with "noisy" or incomplete letter information. However, when the nonwords consisted of items that had several neighbors (thereby making word–nonword discriminations more difficult), ambiguity effects were observed. Subjects appeared to be capable of modulating their response strategy so that when they were in a consistently sparse-neighborhood nonword condition, some decisions could be initiated before reducing the neighborhood alternatives to a single word. In denser neighborhood contexts, however, decisions could not made until all competitors had been suppressed. Furthermore, when the nonwords were of mixed-neighborhood density, ambiguity effects were obtained primarily for those words in which the ambiguous letter position yielded at least one higher frequency neighbor, that is, an interaction between ambiguity and relative neighbor frequency was observed. When the neighborhoods were uniformly dense, on the other hand, ambiguity effects were not qualified by relative neighbor frequency; the presence of any neighbors was sufficient to produce an ambiguity effect. Finally, there were suggestions in the current experiments that a large ratio of friendly to unfriendly neighbors (i.e., the number of neighbors in a word at undelayed positions relative to its neighbors at the delayed position) attenuated the ambiguity effects to some degree.

These results extend previous investigations of neighborhood competition effects in several ways. Grainger and his colleagues (Grainger, 1990, 1992; Grainger et al., 1989) found that words yielding at least one higher frequency neighbor were responded to more slowly than matched words that did not yield any higher frequency neighbors. The interaction between ambiguity and relative neighbor frequency observed in Experiment 1 provides support for Grainger's claim. However, the fact that ambiguity was not qualified by relative neighbor frequency in the dense nonword context of Experiment 2 might be taken to suggest that when subjects adopt a higher discrimination criterion (due to greater task difficulty), then even neighbors that are of lower frequency than the target can be competitive.

Pugh et al. (1994), and Johnson and Pugh (in press) found that neighborhood spread (the number of letter positions yielding neighbors) or higher frequency neighborhood spread (the number of letter positions yielding higher frequency neighbors) was positively correlated with lexical-decision word-response latency. We researchers suggested that this effect was due to unresolved ambiguous letter positions requiring more bottom-up processing than unresolved unambiguous positions; as the number of ambiguous positions increased, a word's average recognition latency increased. The current studies were designed to test the notion that positional ambiguity produces increased processing demands, and the results were clearly supportive. The present data represent the most direct evidence to date that the mechanism behind response delays due to neighborhood spread is the increased time required for the resolution of the ambiguous letters.

The fact that the neighborhood effects observed in the current lexical decision experiments and others appear to be modulated by the specific characteristics of the nonword stimuli (Johnson & Pugh, in press; Pugh et al., 1994) might lead us to question whether the lexical decision task is an appropriate vehicle for examining the word recognition process. It seems clear that lexical decisions can be made at several points along the processing continuum (Balota & Chumbley, 1984; Pugh et al., 1994). However, there are several findings that suggest that when subjects must unambiguously discriminate a target from its neighbors, a process that seems likely to occur in normal reading, competitive neighborhood effects emerge. As noted above, when nonwords yielded large neighborhoods, we observed inhibitory neighborhood spread effects, polysemy effects, and larger frequency effects. When the nonwords were less wordlike, that pattern of results was not obtained (Pugh et al., 1994). The current results appear to tell the same story; ambiguity effects occurred only with the more difficult nonword contexts. We suspect that even when a subject is reading words in context, if a given target must be carefully processed (e.g., if that word is not predictable from context), inhibitory neighborhood effects will be the rule. It may be that the lexical decision task informs us about word recognition if, and only if, the nonword context forces the discrimination of the target from its neighborhood.

The current findings present some challenges to both serial search and activation models but in general are more friendly to the latter class. Search models predict that only higher frequency neighbors should significantly slow the recognition process (Forster, 1976, 1992; Paap et al., 1982, 1987). In Experiment 1, the Ambiguity × Relative Neighbor Frequency interaction seems to be consistent with this view. However, in the dense condition of Experiment 2, neighbors of both higher and lower frequency than the target inhibited processing. This result, if robust, would require the assumption of frequency-ordered search to be relaxed somewhat. Furthermore, search models provide no obvious account for the attenuation of the ambiguity effect observed among stimuli possessing high ratios of friendly to unfriendly neighbors.

The interactive-activation model of McClelland and Rumelhart (1981) appears to be broadly consistent with the results of Experiment 1. Delaying an ambiguous letter position should be more costly than delaying an unambiguous position because of the increased opportunity for intralexical competition effects in the former case. Furthermore, higher frequency neighbors should be more competitive because of their higher resting levels of activation. The Relative Frequency × Ambiguity interaction (Experiment 1) seems to be a natural consequence of such an architecture. However, the failure to obtain this interaction in the dense condition of Experiment 2, even though an ambiguity effect was obtained, poses an apparent challenge to this model as well as to search models. Even if, in response to the more difficult nonwords in the dense condition of Experiment 2, subjects adopted a higher threshold of recognition, a constraint on processing imposed by the relative frequency of the target to its neighbors seems mandatory. This merits further investigation. On the other hand, the constraint on ambiguity effects imposed by high friendly-to-unfriendly-neighbor ratios appears to be quite consistent with the assumptions of the interactive activation model and certainly warrants further investigation as well.

It has been suggested by Andrews (1989, 1992) that neighborhood effects are largely facilitatory in word recognition. It should be remembered that Andrews (1989, 1992) found a facilitatory influence of N in both lexical decision and naming tasks (and in the latter task presumably response bias was not a factor). Nonetheless, the Johnson and Pugh (in press) and Pugh et al. (1994) studies suggested that inhibitory influence comes not from neighborhood size but rather from neighborhood spread, and this variable was not examined in the Andrews studies. On the whole, the current results appear to converge with those of Grainger and his colleagues (Grainger 1990, 1992; Grainger et al., 1989), Johnson and Pugh (in press), and Pugh et al. (1994) in suggesting that when task demands are sufficiently challenging to require full processing of the target stimulus, inhibitory neighborhood effects are observed.

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