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Lexical Access During Eye Fixations in Reading: Effects of Word-Initial Letter Sequence

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Two experiments tested the hypothesis that lexical access in reading is initiated on the basis of word-initial letter information obtainable in the parafoveal region. Eye movements were monitored while college students read sentences containing target words whose initial trigram (Experiment 1) or bigram (Experiment 2) imposed either a high or a low degree of constraint in the lexicon. In contradiction to our hypothesis, high-constraint words (e.g., DWARF) received *longer* fixations than did low-constraint words (e.g., CLOWN), despite the fact that high-constraint words have an initial letter sequence shared by few other words in the lexicon. Moreover, a comparison of fixation times in viewing conditions with and without parafoveal letter information showed that the amount of decrease in target fixation time due to prior parafoveal availability was the same for high-constraint and low-constraint targets. We concluded that increased familiarity of word-initial letter sequence is beneficial to lexical access and that familiarity affects the efficiency of foveal but not parafoveal processing.

In reading a sentence, each component word must be encoded and matched with an appropriate representation in the internal lexicon. Lexical access is often studied by presenting isolated words to subjects looking at the center of a display screen. Reading a line of normal text, however, requires eye movements. Although it is true that all the visual information supporting reading is gathered during fixational pauses and not during eye movements, fixation duration in reading is quite variable, and a word may receive no fixation, one fixation, or more than one fixation. In addition, normal text arrangement allows the possibility of the use of parafoveal as well as foveal information. It turns out that our ability to read fluently requires the presence of parafoveal information: If all letters to the right of the fixated word are unavailable, then reading rate declines markedly (Rayner, Well, Pollatsek, & Bertera, 1982). It is evident that a complete account of reading will need to explain how both foveal and parafoveal information about a word are used to achieve lexical access.

Although parafoveal information is essential for reading fluency, the spatial extent of useable letter information is actually quite limited. During a typical fixation, a reader can acquire detailed information from the fixated word and from the beginning letters of the word immediately to its right. When the first three letters of the word to the right of the fixated word are intact but the letters beyond are replaced by other, visually similar letters, reading rate is only slightly impaired relative to a condition in which the entire word to the right of the fixated word is left intact (Rayner et al., 1982). The implication is that word-initial letter information is largely responsible for facilitation in reading because of parafoveal information. The importance of these word-initial letters is not surprising because they fall closer to the fovea and,

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being flanked by a space on the left, are less subject to the detrimental effects of lateral masking than are more medial letters of the parafoveal word.

A plausible interpretation of facilitation due to word-initial letters in the parafovea is that preliminary letters or letter patterns identified in the parafovea are used in accessing the word when it is brought under foveal regard. This interpretation is consistent with the finding that word-initial letter information presented parafoveally on one fixation facilitated the naming of a word available foveally on the next fixation (Rayner, 1978; Rayner, McConkie, & Ehrlich, 1978; Rayner, McConkie, & Zola, 1980). An alternative explanation is that purely semantic expectations are generated while a word is still in the parafovea. The latter explanation is doubtful, however. Inhoff and Rayner (1980; Inhoff, 1982) showed that the presence of a disambiguating word in the parafovea did not affect judgments about the meaning of an ambiguous word presented in the fovea. In another study, when a visual mask was moved in synchrony with the reader's point of fixation, the errors made in reporting the sentence tended to be visually rather than semantically similar to the words beyond the mask (Rayner, Inhoff, Morrison, Slowiaczek, & Bertera, 1981).

Word-initial letters have been accorded a role of particular importance in studies of lexical access of foveally presented words. Word recognition is hurt less by disruptions of the final letters of a word than by disruptions of the initial letters (Bruner & O'Dowd, 1958; Oleron & Danset, 1963; Pillsbury, 1897). Delaying the presentation of an initial segment of a word is more detrimental to word recognition than is delaying the presentation of a final segment (Lima & Pollatsek, 1983; Mewhort & Beal, 1977). Some recent models have proposed that the lexicon is contacted on the basis of word-initial information alone (Marslen-Wilson & Welsh, 1978; Taft & Forster, 1976; Taft, 1979). In the model of Marslen-Wilson, developed to account for lexical access in speech perception, the initial few phonemes of an input word activate a cohort set in the lexicon. The cohort set contains a representation for every word that begins with the initial phonemes that have been heard. As more of the stimulus word is heard, the size of the cohort set is progressively reduced until only one word candidate remains, at which point the word is recognized. For many words, recognition occurs before the entire word is heard. There is evidence that word monitoring latency is often less than word duration (Marslen-Wilson & Tyler, 1980) and that listeners are less sensitive to pronunciation errors that occur after the point of recognition (Marslen-Wilson & Welsh, 1978).

The present study focused on one version of a hypothesis of lexical access based on the initial letter sequence of a word. The constraint hypothesis maintains that ease of lexical access increases whenever the size of the set of potential word candidates is particularly limited by beginning letter information. In a study of conscious word guessing, for example, Broerse and Zwaan (1966) asked subjects to guess a seven-letter noun based on only a few consecutive letters printed in their appropriate positions. They found that solution time increased when the given letter sequence was compatible with a large number of word alternatives. In our experiments, we varied the degree of lexical constraint imposed by a target word's initial letter sequence in order to discover whether such a phenomenon underlies lexical access in normal fluent reading. Subjects read sentences like the following:

The weary *dwarf* hated his job.
The weary *clown* hated his job.

DWARF is a high-constraint target word, whereas CLOWN is the corresponding low-constraint target word. DWARF is considered high constraint because it shares its initial trigram DWA with few other words; CLOWN is low constraint because its initial trigram CLO appears in many words, such as CLONE, CLOSET, CLOSE, CLOUD, and CLOD. The first prediction of the constraint hypothesis is that a word like DWARF should receive less viewing time than one like CLOWN, because the former has an initial sequence delineating a much smaller set of word alternatives than the latter. The constraint hypothesis is compatible with the cohort model of Marslen-Wilson except that it remains neutral with respect to whether the letters in a word are processed serially from left to right, or in parallel, with an attentional bias favoring the word-initial letters. The cohort model does, however, make the same prediction as the constraint hypothesis, because high-constraint words tend to have recognition points occurring in more leftward letter positions than those of low-constraint words.

If a word's beginning few letters are crucial to lexical access, and if the detailed letter information obtainable from a word to the right of fixation is largely confined to its first three letters, then it is conceivable that much of the information necessary to identify a high-constraint word is obtainable while the word is still in the parafovea. If the role of parafoveal information is to limit the size of the candidate set in the lexicon, then the amount of facilitation due to parafoveal preview of a target word should be a function of the amount of constraint imposed by the word-initial letters. The second prediction of the constraint hypothesis, therefore, is that parafoveal availability of a target word will reduce subsequent foveal target viewing time to a greater degree if the target word is high constraint than if it is low constraint. To test this prediction, eye-contingent display changes were used to present sentences in three viewing conditions, each allowing a different amount of parafoveal letter information. In the first viewing condition, termed the *one-word window*, readers were deprived of parafoveal letter information to the right of the fixated word; these letters were replaced by *X*s. In the second condition, the *two-word window*, letters to the right of the next word beyond the fixated word were replaced by *X*s. In the third condition, all information was normally intact. Fixation durations in the latter two conditions can be subtracted from those in the first condition to assess the decrease in target viewing time due to parafoveal preview. The constraint hypothesis does not predict that low-constraint words will receive no benefit from parafoveal availability, but that the benefit will be less for low-constraint words than for high-constraint words.

In these experiments, constraint was first indexed by simply counting the different words beginning with a given letter sequence. A second, more sophisticated index of constraint took word length into account. Information about the length of words in the parafovea becomes available early in the current fixation (Pollatsek & Rayner, 1982). Perhaps the lexical access process uses word-length information in conjunction with initial letter sequence, so that all members of a set of word candidates have the same length. By this account, CLOUD, CLOSE, and CLONE are in the same set as CLOWN, but CLOD and CLOSET are not. The stimuli used in these experiments, therefore, were designed so that the high-constraint member of each target pair was higher in constraint than the low-constraint member whether or not word length was used to further restrict the set of possible word candidates.

The major measure of viewing time used in these experiments was first fixation duration. Because it includes only the duration of the very first fixation placed on a target word, this measure is presumed to be sensitive to early lexical processing. Gaze durations were also tabulated. These include the duration of the first fixation plus any additional time spent fixating the target word before fixating another word. Gaze durations are more likely than first fixation durations to include time due to processes occurring after lexical access (Inhoff, 1984; Just, & Carpenter, 1980).

Experiment 1

Method

Subjects. Eighteen students at the University of Massachusetts were paid to participate. All subjects had normal vision or were able to read the sentences without the aid of corrective lenses.

Materials. Stimuli were drawn from a set of 42 pairs of sentences. (See Appendix for the complete list). The two members of each sentence pair were identical except for the target word, which was either a high-constraint word or a low-constraint word. A high-constraint word has an initial trigram compatible with a very small set of word candidates, whereas a low-constraint word has an initial trigram compatible with a much larger set of word candidates.

Degree of lexical constraint was assessed in several ways. First, constraint was indexed by simply counting the number of different words listed in Kučera and Francis (1967) that began with the same trigram as the target word.[1] The high-constraint targets had a mean trigram count of 4.8 words (range = 1 to 14), indicating that, on average, the initial trigram of a high-constraint

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[1] The target word itself was included in all calculations of constraint measures in Experiments 1 and 2.

word was the initial trigram of 4.8 words in the Kučera and Francis list. The low-constraint target words had a mean trigram count of 80.4 words (range = 23 to 206). The trigram count of the low-constraint member of each target pair was at least 22 units greater than that of the high-constraint member.

The second measure of constraint was like the first except that it took word length into account. By this measure, constraint was indexed by counting the number of different words in the Kučera and Francis list that both began with the same trigram as the target word and had the same number of letters as the target word. The high-constraint targets had a mean length-sensitive trigram count of 1.2 words (range = 1 to 3); the low-constraint targets had a mean length-sensitive trigram count of 9.0 words (range = 2 to 20). Every high-constraint word had a length-sensitive count less than that of its low-constraint counterpart.

The two initial-trigram counts described above were based on word types, not word tokens, because it is types that are of direct relevance to the constraint hypothesis. By these counts, the numbers assigned to each target word reflected the number of *different* words beginning with the same trigram rather than the frequency of that word-initial trigram in running text. However, initial-trigram frequencies[2] were also taken into consideration when target word pairs were being selected. The resulting set of target word pairs had the property that every high-constraint word had not only a lower initial-trigram count than its low-constraint counterpart but also a lower initial-trigram frequency than its low-constraint counterpart (not taking word length into account). Furthermore, this relation also held for the length-sensitive trigram frequencies[3] of 41 of the 42 target pairs.[4]

The high- and low-constraint members of each target pair were exactly matched on grammatical category (part of speech), number of letters, and number of syllables. Target words ranged in length from four to seven letters (mean = 5.2) and had one or two syllables (mean = 1.5). The members of each pair were closely matched on word frequency (Kučera & Francis, 1967); the mean frequency for both the set of high-constraint targets and the set of low-constraint targets was 10.5 per million. In addition, care was taken to make a given sentence frame neither more nor less contextually predictive of the high-constraint target word than of the low-constraint target word. In no case was a target word anomalous with respect to its sentential context, and to lessen any possible difference in predictability of a target word based on sentential context prior to the target, the target appeared early in the sentence, usually in the second or third position. The initial position in a sentence was avoided because the first fixation on a line of text tends to be unusually long (Rayner, 1977).

Each stimulus sentence was 42 or fewer character spaces in length, occupying one line on the cathode-ray tube (CRT) display screen.

Design. Two lists were constructed, each containing 42 experimental sentences. Each list contained 21 high-constraint sentences and 21 low-constraint sentences. The low-constraint target member of a sentence pair appeared in one list, and its high-constraint target mate appeared in the other list, so that no list contained both members of a sentence pair. Half of the subjects were assigned to each list.

Each list was segmented into three blocks of 14 sentences, half containing high-constraint targets and half containing low-constraint targets. Each block of 14 sentences was presented in one of three different visual presentation conditions, the sequence of which was counterbalanced across subjects. Within a block, the seven high-constraint and seven low-constraint sentences were presented in random order.

The three visual presentation conditions were the one-word window, the two-word window, and the full-line conditions. In the one-word window condition, all letters in words to the right of the fixated word were replaced with *X*s, while interword spaces were maintained. During the saccade in which the subject shifted his or her eyes to a new fixation location, the display changed immediately, so that the window of intact text was always contingent on fixation location. The two-word window condition presented the currently fixated word plus one word to the right of the fixated word, while letter information beyond was replaced by *X*s. Again, all interword spaces were maintained. In the full-line condition, the sentence was presented normally intact throughout the trial.

Before reading any experimental sentences, each subject completed 16 trials with practice sentences to become familiar with the procedure. Two additional practice sentences were read at the start of each of the three trial blocks.

Apparatus. A bite plate prepared for each subject was used to reduce head movements during the experiment. The subject's eyes were held 46 cm from a Hewlett-Packard 1300A CRT that was used to present each sentence. The CRT has a P-31 phosphor with the characteristic that removing one character results in a drop to 1% of maximum brightness in .25 ms. Three character spaces equals 1° of visual angle. A black theater gel covered the screen to enhance sharpness, and the CRT was adjusted to a comfortable brightness level for each subject. Sentences were presented in lowercase.

Eye movements were recorded with a Stanford Research Dual Purkinje Eyetracker interfaced with a Hewlett-Packard 2100A computer that controlled the experiment. The eyetracker has a resolution of 10′ of arc, and the output is linear over the angle subtended by a line of text. The computer sampled the eyetracker signal every millisecond, and each 4 ms of eyetracker output was compared with the output of the previous 4 ms to determine whether the eyes were fixed or moving. Display

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[2] Initial-trigram frequencies were calculated by first taking each word that began with the same trigram as the target and then weighting it by its word frequency. For the overall initial-trigram frequency measure, all the words beginning with a given trigram were weighted and entered into the sum.

[3] For the length-sensitive initial-trigram frequency measure, only the words with the same initial trigram *and* length as the target were included in the frequency-weighted sum.

[4] The single exception was the target pair KISS (high constraint) with a length-sensitive initial-trigram frequency of 17 and SLAP (low constraint) with a length-sensitive frequency of 16.

changes in the one-word and two-word window conditions were accomplished within 5 ms of each saccade. The computer kept a complete record of the duration, sequence, and location of each fixation.

Procedure. Subjects were tested individually and were given instructions about the experimental procedure. No information about the nature of the target words or viewing conditions was divulged. A one-dimensional calibration procedure at the start of the experiment ensured that the eyetracker was accurately determining the point of the subject's fixation.

After calibration, three crosses were displayed, one at the left, one at the center, and one at the right of the screen. The subject's fixation point was marked by a fourth cross moving in synchrony with the eyes. The subject was instructed to superimpose the fixation-marking cross over the left-hand cross, and when this was accomplished, the experimenter presented the first sentence. The left-hand cross coincided in position with the first letter of the sentence. When the subject finished reading a sentence, he or she pressed a key that removed the sentence from the screen. The cycle of superimposing the fixation marker on the left-hand cross, displaying a sentence to be read, and pressing a key to remove the sentence was repeated for each trial.

Subjects were told to read each sentence for normal comprehension. To ensure comprehension, they were occasionally asked to paraphrase the sentence they had just read.

Data analysis. Two dependent variables were of interest: first fixation duration on the target word and gaze duration on the target word. The variable of primary interest was first fixation duration, which is simply the duration of the very first fixation a subject placed on each target word. Gaze duration on a target word consists of the cumulated viewing time resulting from the first fixation on the target and any other fixations on the target before another word is fixated.

A target word was considered fixated if the subject's fixation point fell on one of its component letters or on the space immediately preceding it. Fixations of more than 800 ms were discarded because these unusually long fixations are often due to eye blinks.

Data were analyzed in both subject analyses and item analyses. A data point in the subject analysis consisted of the mean value of the dependent measure (first fixation duration or gaze duration) for the seven high-constraint or seven low-constraint sentences that the subject saw in each of the three viewing conditions. Thus, a data point was usually based on seven observations; however, it was sometimes based on less than seven observations because of discarded data due to abnormally long fixations or to track losses. Each subject provided exactly six data points for use in the subject analysis. Similarly, in the item analysis, a data point was the mean value for each item in each of the six possible combinations of target type and viewing condition; each item yielded exactly six data points for use in the item analysis.

Results and Discussion

First fixation durations. The constraint hypothesis predicts that words beginning with high-constraint trigrams should be accessed in the lexicon more quickly than words beginning with low-constraint trigrams, and this should be reflected in shorter first fixations on high-constraint target words than on low-constraint target words. Mean first fixation durations on target words are presented in Table 1. Although there was a reliable effect of constraint, the direction of the effect was exactly opposite to that predicted by the constraint hypothesis: High-constraint words received *longer* first fixations (255 ms) than did low-constraint words (239 ms), $F'_{min}(1, 53) = 4.69$, $p < .05$. It appears that a word beginning with a rare trigram is accessed more slowly, not more quickly, than one beginning with a more common trigram.

Table 1
First Fixation Duration and Gaze Duration (in milliseconds) on High- and Low-Constraint Target Words as a Function of Window Size (Experiment 1)

	Constraint			
	High		Low	
Window size	FFD	GD	FFD	GD
1 word	283	315	271	302
2 words	252	264	228	256
Full line	231	256	219	249

Note. FFD = first fixation duration; GD = gaze duration.

The second prediction of the constraint hypothesis is that the processing of a high-constraint word would benefit more from its presence in the parafovea prior to fixation than would the processing of a low-constraint word. This prediction was also refuted by the first fixation duration data. Although the reliable effect of window size does indicate advantages due to parafoveal preview of target words, $F'_{min}(2, 96) = 11.47$, $p < .01$, the lack of a reliable interaction of window size and constraint, ($F < 1$ both by items and by subjects) indicates that the size of the parafoveal preview advantage did not depend on the level of constraint. The mean of the fixation durations in the two-word window and the full line was subtracted from the fixation duration in the one-word window to yield a measure of the parafoveal preview advantage. The mean parafoveal preview advantage was, in fact, similar for high-constraint words (41 ms) and low-constraint words (48 ms).

Both components of the constraint hypothesis appear to be invalid. A word beginning with a rare trigram received a longer first fixation than one beginning with a common trigram, despite the fact that the latter shares its initial trigram with many other words in the lexicon. In addition, a word beginning with a common trigram benefitted from parafoveal preview about as much as did a word beginning with a rare trigram, indicating that the parafoveal processing of a word is unaffected by the degree of lexical constraint imposed by its initial trigram.

Gaze durations. The pattern of the gaze duration data (presented in Table 1) corresponded quite closely to the pattern of the first fixation duration data. There was a trend toward shorter gaze durations on low-constraint words (268 ms) than on high-constraint words (278 ms), although this difference was not statistically reliable, $F(1, 17) = 2.95$, $p < .11$ by subjects, and $F(1, 41) = 1.98$, $p < .17$ by items. As in the first fixation duration data, there was a reliable effect of window size, indicating advantages due to parafoveal preview, $F'_{min}(2, 97) = 8.82$, $p < .01$, and there was no reliable interaction of window size and constraint ($F < 1$) on both the subject analysis and the item analysis. For gaze durations, the parafoveal preview advantage relative to the one-word window condition averaged 56 ms for the high-constraint words and 49 ms for the low-constraint words. Neither the gaze duration results nor the first fixation duration results offer support for the two components of the constraint hypothesis.

The fact that the superiority of low-constraint words over high-constraint words was statistically reliable only in the first fixation duration data suggests that type of initial trigram affected an early stage of lexical processing. The effect became diluted when the more inclusive gaze durations were considered. The gaze duration on a word exceeds its first fixation duration when the word receives two or more fixations in succession, so that gaze durations are more likely than first fixation durations to include some time due to operations occurring after lexical access. The observed superiority of low-constraint words even in the one-word window condition indicates that type of initial trigram affected early target processing in the fovea. However, type of trigram did not seem to affect the size of the advantage due to parafoveal processing of the target. The degree of benefit accruing from parafoveal availability prior to fixation was similar for high- and low-constraint target words, suggesting that parafoveal processing is quite different from early foveal processing.

Experiment 2

The findings of Experiment 1 contradict the constraint hypothesis. A word beginning with a relatively rare trigram shares that initial trigram with few other words in the lexicon, and yet it takes longer to access than a word with a more common word-initial trigram. Furthermore, the effectiveness of a word's parafoveal processing is uninfluenced by the degree of lexical constraint imposed by its initial trigram.

In Experiment 1, the initial trigram was chosen as the constraint index because of previous research indicating the importance of the first three letters of the word to the right of the fixated word (Rayner et al., 1982). However, research has also indicated facilitation due to the first two letters of the word to the right of fixation. For example, Rayner et al. (1980) showed that information about a parafoveal word facilitated naming a word brought into foveal vision if both words shared the same initial bigram or trigram. Experiment 2 was designed to test the constraint hypothesis on target word pairs in which constraint was indexed by initial bigram count.

Although most of the target pairs in Experiment 1 had the property that the high-constraint member of the pair was high constraint regardless of whether constraint was indexed by bigrams or trigrams, 26% of the pairs did exhibit a reversal, that is, the word whose constraint was the higher of the pair when indexed by trigram became the lower-constraint member of the pair when indexed by bigram. Because of possible problems of interpretation due to such reversals, we gathered new target pairs, in which no reversals occur, for Experiment 2. In this experiment, the two members of each target pair differed greatly in initial bigram count, and the initial trigram count of the high-constraint member was less than or equal to that of the low-constraint member.

Experiment 2 differed from Experiment 1 in two other ways. First, the target words were higher in word frequency than those used in Experiment 1. Higher frequency words were selected because of the finding that readers tend to make more effective use of parafoveal information from high-frequency words than from low-frequency words (Inhoff, Lima, & Rayner, 1983). Second, the full-line condition of Experiment 1 was replaced with a window condition, which allowed less parafoveal information. We limited parafoveal information in Experiment 2 to letters in the word immediately to the right of the fixated word because the full-line condition of Experiment 1 led to a smaller difference between high and low constraint words (12 ms) than did the two-word window (23 ms).

Method

Subjects. Eighteen students at the University of Massachusetts were paid to participate. All subjects had normal vision or were able to read the sentences without the aid of corrective lenses.

Materials. The 42 pairs of sentences were constructed in a similar fashion to the 42 pairs of sentences used in Experiment 1, with the exception that bigram counts rather than trigram counts were used as the primary determiners of whether a target word was high constraint or low constraint. (See Appendix for a complete list.) In Experiment 2, a high-constraint word had a mean bigram count of 35.2 words (range = 4 to 118), indicating that, on average, the initial bigram of a high-constraint word was the initial bigram of 35.2 words listed in Kučera and Francis (1967). The low-constraint targets had a mean bigram count of 361.9 words (range = 209 to 814). These bigram counts were available in published norms, where they are referred to as *initial bigram versatilities* (Solso, Juel, & Rubin, 1982). The low-constraint member of a target pair began with an initial bigram whose count was at least 108 units greater than that of the corresponding high-constraint word. Length-sensitive initial bigram counts were also calculated. The high-constraint targets had a mean length-sensitive bigram count of 2.8 words (range = 1 to 7); the mean for the low-constraint targets was 41.1 words (range = 9 to 96). Every high-constraint word began with a bigram whose length-sensitive count was less than that of the corresponding low-constraint word.

In addition, the word pairs had the property that the initial trigram count of a high-constraint word was less than or equal to the initial trigram count of the corresponding low-constraint word. The high-constraint words had a mean initial trigram count of 15.3 (range = 1 to 62), and the low-constraint words had a mean initial trigram count of 55.1 (range = 9 to 206). Furthermore, 41 of the 42 target pairs had the same relation when word length was taken into account.[5] The high-constraint words had a length-sensitive initial trigram count of 1.4 (range = 1 to 3), and the low-constraint targets had a mean of 5.6 (range = 1 to 38).

As in Experiment 1, type counts rather than token counts were of primary importance in determining degree of constraint. However, initial-bigram frequencies were also taken into account, with the result that all 42 target pairs had a low-constraint member with an initial-bigram frequency higher than that of the corresponding high-constraint member; this was true regardless of whether or not word length was taken into consideration. In addition, initial-trigram frequencies showed the appropriate relation for all 42 target pairs (not considering word length) and for 40 of the 42 target pairs (considering word length).[6]

The high- and low-constraint members of each target pair were exactly matched on grammatical category and on number of letters (range = 4 to 10, M = 5.1). Pair members were closely matched on number of syllables (range = 1 to 3, M = 1.7) and on word frequency; the mean frequency of the high-constraint words was 105.5 per million, and the mean frequency of the low-constraint words was 105.0 per million (Kučera and Francis, 1967). Care was taken to ensure that high- and low-constraint target words were equally compatible with their sentential context. Targets usually appeared in the second or third position in the sentence.

Sentences, never more than 42 character spaces in length, occupied one line on the CRT.

Design, apparatus, and procedure. Design, apparatus, and procedure were nearly identical for Experiments 1 and 2. The only difference was in viewing conditions. The full-line condition used in Experiment 1 was replaced with a one-word-plus-three-letters window condition in Experiment 2. In this window condition, the fixated word and words to the left were intact. The word to the right of the fixated word had its first three letters intact, but the remaining letters of the word and the letters of the words to the right of that word were replaced by Xs. Interword spaces were maintained throughout the experiment.

Results and Discussion

First fixation durations. The first fixation duration data, presented in Table 2, largely replicated those of Experiment 1: Low-constraint words received shorter first fixations than did high-constraint words. Target words beginning with low-constraint bigrams received first fixation durations averaging 251 ms, whereas target words beginning with high-constraint bigrams received average first

[5] The exception is CITY (3)–SIDE (1).

[6] The exceptions are CITY (401)–SIDE (380) and AUNT (22)–PIPE (20).

Table 2
First Fixation Duration and Gaze Duration (in milliseconds) on High- and Low-Constraint Target Words as a Function of Window Size (Experiment 2)

	Constraint			
	High		Low	
Window size	FFD	GD	FFD	GD
1 word	282	302	268	306
1 word + 3 letters	270	295	256	272
2 words	246	267	230	254

Note. FFD = first fixation duration; GD = gaze duration.

fixation durations of 266 ms. This difference was reliable in both the subject analysis, $F(1, 17) = 14.25, p < .002$, and the item analysis, $F(1, 41) = 4.17, p < .05$, although it missed significance on F'_{min}, $F'_{min}(1, 57) = 3.3, p < .10$.

As in Experiment 1, there was a reliable effect of window size such that the presence of parafoveal information lowered first fixation durations on target words, $F'_{min}(1, 67) = 6.18, p < .025$. Most crucial to the constraint hypothesis is the absence of an interaction of window size and constraint ($F < 1$ both by subjects and by items), a finding that once again implies that readers do not gain more useful parafoveal information from high-constraint words than from low-constraint words. When the one-word-plus-three letters and the two-word window conditions were averaged, the mean parafoveal preview advantage relative to the one-word-window condition was similar for words beginning with high-constraint bigrams (24 ms) and words beginning with low-constraint bigrams (25 ms). The parafoveal advantages in Experiment 2 were smaller than those in Experiment 1 because Experiment 1 included a full-line condition, presenting more parafoveal information than was available in any of the window sizes employed in Experiment 2.

The target words used in Experiment 2 had the property that the high-constraint member of a target word pair had an initial bigram count less than of the low-constraint member *and* an initial trigram count less than or equal to that of the low-constraint member. Therefore, these word pairs should have provided favorable conditions for discovering a first fixation duration decrease due to rare initial letter sequence, as predicted by the constraint hypothesis. Because Experiment 2, in fact, joined Experiment 1 in opposing the constraint hypothesis, we can conclude that the results of Experiment 1 were not due to the use of some high-constraint target words whose initial bigram counts were greater than those of their corresponding low-constraint target words. Furthermore, the limited parafoveal information available in the parafoveal conditions of Experiment 2 did not produce an effect of constraint on the size of the parafoveal preview advantage, suggesting that the similar finding in Experiment 1 was not due to information available beyond the target word in the full-line condition.

Gaze durations. The gaze duration results, shown in Table 2, provided no support for the constraint hypothesis. Low-constraint words received somewhat shorter gaze durations (277 ms) than high-constraint words (288 ms), but the difference missed statistical significance, $F(1, 17) = 4.19, p < .06$ by subjects, and $F(1, 41) = 1.53, p < .22$ by items. There was a reliable effect of window size, indicating advantages due to parafoveal preview, $F'_{min}(2, 58) = 4.23, p < .025$. In contrast to Experiment 1, there was some tendency toward an interaction of window size and constraint. Specifically, high-constraint target words received somewhat shorter gaze durations than did low-constraint targets in the one-word window condition. In the two conditions allowing parafoveal preview, high-constraint words received longer gaze durations than did low-constraint words, particularly in the one-word-plus-three letter window condition. However, this interaction failed to reach statistical significance, $F(2, 34) = 1.15, p < .33$ by subjects, and $F(2, 82) = 1.84, p < .17$ by items. And when the two parafoveal window conditions were averaged, the mean parafoveal advantage relative to the one-word window was 21 ms for the high-constraint words and 43 ms for the low-constraint words, a pattern opposite to that predicted by the constraint hypothesis.

As in Experiment 1, low-constraint words were processed more quickly than high-constraint words, and this effect reached statistical significance in the first fixation duration data but not in the gaze duration data. The observed superiority of low-constraint words is diluted when the dependent measure becomes more inclusive and is more likely to be sensitive to postlexical processes. Surprisingly, in Experiment 2 the pattern of gaze duration data did not closely parallel that of the first fixation data, but the gaze duration measure in both experiments was quite variable and appeared to be a less sensitive indicator of parafoveal preview effects than was first fixation duration. We can once again conclude that the advantage of low-constraint words relative to high-constraint words reflects faster early lexical processing due to a more common word-initial letter sequence.

Combined analysis of Experiments 1 and 2. The lack of a statistically reliable interaction between constraint and window size has been taken as evidence against the constraint hypothesis. In order to strengthen the basis of this conclusion, which rests on accepting the null hypothesis, we combined the data from the one-word window and the two-word window across Experiments 1 and 2 and perfored ANOVAs over all subjects. Even with these more powerful analyses, based on 36 subjects instead of 18, the interaction between constraint and window size never approached significance for either the first fixation durations, $F(1, 35) = 1$, or the gaze durations, $F(1, 35) < 1$. Admittedly, any interaction we might have observed would have been very small, in view of the small size of the main effect of constraint (in the range of 10–16 ms), but we can cautiously conclude that no evidence of such an interaction was found.

General Discussion

The results reported here invalidate the constraint hypothesis as an explanation of lexical access during foveal and parafoveal viewing of words in reading. This hypothesis claimed that lexical access relies on the word-initial letter sequence to constrain the set of possible word candidates that need to be considered. Under this hypothesis, lexical access can be initiated while the word in question is yet to be fixated, because it is known that readers acquire information from the beginning two or three letters of a word to the right of fixation (e.g., Rayner et al., 1982). Both claims of the constraint hypothesis were proved false. First, a high-constraint word such as DWARF, whose initial bigram or trigram is compatible with a very small set of word candidates, received *more,* not less, fixation time than did a low-constraint word such as CLOWN, whose initial bigram or trigram is compatible with a larger set of word candidates. Second, the size of the decrease in fixation time due to prior parafoveal availability of the target was about the same for both types of target words. If lexical access had been initiated in the parafovea on the basis of the degree of lexical constraint inherent in the word-initial letter sequence, then more facilitation should have been observed for the high-constraint targets.

We can also reject the more sophisticated hypothesis that lexical access relies on word-length information in conjunction with word-initial letter sequence information to narrow the set of possible candidates in the lexicon. One of the measures of lexical constraint we employed was length sensitive, so that the high-constraint words were compatible with a smaller set of word candidates than the low-constraint words even when word length was added as a source of constraining information. The finding that the high-constraint words received longer first fixations than the low-constraint words therefore rules out even a length-sensitive view of lexical constraint based on initial letter sequence.

Before we abandon the constraint hypothesis, it might be worthwhile to consider the implications of an even more sophisticated index of constraint. Perhaps the lexical access process uses semantic and syntactic context to further narrow the set of word alternatives. Under this view, in reading THE WEARY CLOWN HATED HIS JOB, CLOWN and CLONE are likely to be in the candidate set for CLOWN, but CLOSET, CLOBBER, and CLOUT are not. Reassessing the constraint levels of our target words by including the criterion of contextual likelihood would narrow the difference between the high-constraint and low-constraint targets, but it would not eliminate the constraint difference entirely. The sentence pairs were designed to minimize context effects: Each target was entirely appropriate in its context, and targets were placed early in the sentence to avoid differences in the predictability of the target given the prior context. In any event, our finding that high-constraint words take significantly *longer* to process than low-constraint words would not follow from the constraint hypothesis even if the constraint differences were narrowed by including context as a factor. It can quite safely be concluded, then, that the constraint hypothesis itself is incorrect.

Our results indicate that the constraint hypothesis must be turned on its head: It is *familiarity* of a word's initial letter sequence that facilitates word identification. The low-constraint words have initial letter sequences found in more words in the lexicon (and more words in running text) than do the high-constraint words. Readers therefore have a greater amount of exposure to these letter sequences and thus are more efficient in identifying words containing them. A corroborative result was reported in the lexical decision study of Stanners and Forbach (1973), who found that words with common word-initial bigrams (low-constraint words in our terminology) were classified more quickly than those with less common word-initial bigrams (our high-constraint words). Unfortunately, the finding could not be unequivocally attributed to bigram familiarity because this factor was highly correlated with word frequency. Interestingly, however, classification of pronounceable nonwords was slowed when the initial bigram was familiar, suggesting that subjects were so highly attuned to processing familiar initial letter sequences of words that it was difficult to respond *nonword* to letter strings containing them. Our findings demonstrate that subjects are sensitive to familiar word-initial bigrams and trigrams in normal reading and not just under the stringent demands of the lexical decision task. In addition, the processing superiority of words beginning with familiar bigrams and trigrams cannot be solely due to the usual confounding of letter sequence familiarity with word frequency in natural language, because in our experiments, each low-constraint word and its high-constraint counterpart were closely matched on word frequency.

The familiarity advantage we observed is consistent with the general claim that word identification in fluent reading is fast and accurate because it skillfully exploits the orthographic structure of the language: Letters that often co-occur in familiar configurations can be perceived more efficiently than letters co-occurring in unusual configurations, and, because of the processing bias favoring word-initial letters, word-initial orthographic structure can exert a strong effect on the speed with which lexical access is achieved. Effects of orthographic structure have been abundantly documented. Performance on various tasks requiring visual processing is generally faster or better for orthographically legal nonwords than for orthographically illegal ones (e.g., Carr, Posner, Pollatsek, & Snyder, 1979; Gibson, Pick, Osser, & Hammond, 1962; Krueger, 1970). Meaningfulness, therefore, is not required for the exploitation of orthographic structure, a fact that suggests orthography exerts its effect prior to contact with the lexicon. The present findings have the interesting implication that some words are more wordlike than others. Low-constraint words were processed more quickly than high-constraint words, just as wordlike nonwords are processed more quickly than nonwordlike nonwords.

It might be argued that our results are attributable not to orthographic structure per se but to regularity of pronunciation. Orthographic structure is closely linked with spelling–sound correspondence; it is virtually impossible to devise an orthographically legal nonword that is not pronounceable. And, although all words are pronounceable, those with regular grapheme–phoneme correspondences are recognized more quickly than those with irregular grapheme–phoneme correspondences (Baron & Strawson, 1976; Gough & Cosky, 1977; Parkin, 1982; Stanovich & Bauer, 1978). Perhaps our familiarity advantage was due to a preponderance of highly irregular words among the high-constraint targets. Informal inspection of our stimulus lists (see Appendix) does not support this speculation, however. Allowing that the functional graphemes in English are often patterns of two or more letters (e.g., PH, GH) and that their regular pronunciations are highly dependent on their position in a word, their letter environments, and morpheme boundaries (Venezky, 1970), few of the target words are highly irregular. The most obviously irregular words in Experiment 1 are PSALM, TYRANT, MYTH, and YACHT (high constraint) and COUSIN, SWAN, and SOUP (low constraint). In Experiment 2, the obviously irregular words appear to be ECHO, EIGHT, and OCEAN (high constraint) and BREAK, DEFY, HEAVY, and TOMB (low constraint). GNOME and GHOST are quite regular because GN and GH have invariant pronunciations in word-initial position. The high-constraint targets thus appear to be more unusual in their visual orthographic structure than in the regularity of their grapheme–phoneme correspondence.

The goal of the present study was to explain how parafoveal and foveal information are combined in lexical access. We have proposed that familiarity of word-initial letter sequence facilitates lexical access because orthographic structure aids the processing of letter information. The results, however, suggest that orthographic structure exerts its effect on word identification only when the target word is in the fovea. The familiarity effect was of similar size regardless of whether or not the target had been available in the parafovea prior to fixation. Although there were significant reductions in first fixation duration on target words due to prior parafoveal availability, the size of the reduction did not depend on familiarity of word-initial bigram or trigram. If lexical access were initiated on the basis of the identification of familiar word-initial letter sequences in the parafoveal region, then the reduction in first fixation duration attributable to prior parafoveal availability should have been greater for low-constraint targets than for high-constraint targets, and this was not the case.

Our findings disprove the constraint hypothesis, which maintained that lexical access is fastest when the word-initial letter sequence constrains a very small set of candidates in the lexicon. Instead, it appears that in reading, access is fastest when the word-initial letter sequence is compatible with a large set of lexical candidates. This finding implies that the cohort model of lexical access in speech perception (Marslen-Wilson & Welsh, 1978) cannot be adopted to explain lexical access in reading. The cohort model states that lexical access entails the activation of a cohort set of words that is sequentially narrowed down until only a single word candidate remains, at which point the word is recognized. Because a high-constraint word usually has its recognition point occurring in a more initial position than a low-constraint word, the cohort model predicts faster lexical access for high-constraint words. It is possible that the cohort model is more applicable to listening than to reading because of the sequential, continuous nature of the speech stream. An experiment contrasting high-constraint and low-constraint words in an auditory task would constitute a powerful test of the cohort model in speech perception.

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(*Appendix follows on next page*)

Appendix

Stimulus Sentence Pairs

Each of the following sentences is shown with the high-constraint target word above the corresponding low-constraint target word.

Experiment 1:

The three orphans/infants lived with their aunt.

The expensive oysters/cashews were a success.

She might kick/slam the door if she is angry.

A restless zebra/camel had escaped from the zoo.

The mean tyrant/pastor reprimanded the people.

Those gawky/lanky youths are often teased.

My young sister/cousin played with her toys.

Beautiful fuzzy/silky cloth covered the chair.

The ancient myth/tale fascinated the listeners.

The sudden eerie/scary cries startled us.

One critical phrase/clause worried the lawyer.

The costly gifts/dolls cluttered the playroom.

The extremely soggy/murky weather dismayed us.

We shall carefully bake/pare the apples.

The damaged yacht/skiff remained afloat.

Several hefty/bulky cartons have disappeared.

The enormous bubbles/turtles moved very slowly.

A lovely psalm/chant was part of the ceremony.

The clever puzzle/slogan soon became popular.

We saw an unusual pebble/spider in the garden.

The tasty cake/soup was made by the chef.

The absolute zenith/climax of my career had come.

You should poach/grate the eggs now.

She felt dizzy/shaky if she drank too much beer.

The deafening buzz/roar subsided shortly.

The magical gnome/steed had amazing powers.

Abundant fuel/coal is no longer available.

A single ounce/slice of cheese was left.

The damaged skates/shirts were returned.

That homemade jelly/gravy tasted delicious.

The weary dwarf/clown hated his job.

The timid awkward/scrawny boy was without a date.

A pleasant voyage/harbor was the captain's goal.

His favorite tavern/saloon would soon be open.

The little bauble/morsel seemed to satisfy her.

An unexpected noise/crash awakened them.

Fresh juice/cream always accompanied breakfast.

The majestic lake/tree was near our cabin.

We ordered cider/chili at the restaurant.

The resounding kiss/slap surprised them both.

Her shiny gown/mask attracted many stares.

His beloved fawn/swan followed him everywhere.

Experiment 2:

They practice gymnastics/basketball for hours.

We shall ignore/survey the problem.

The lovely lyrics/ballad stirred their emotions.

The tall ghost/cliff frightened the governess.

You cannot equal/break my swimming record.

The sour odor/pill was very unpleasant.

Their vulgar/homely brother was a pest.

The negotiator may yield/argue the point.

The loud echo/bang was heard for miles around.

The dramatic essay/movie was very effective.

The woman's umbrella/telegram was on the desk.

We knew that urgent/heroic action was needed.

The boy will obey/defy his mother's commands.

They reached the ultimate/critical conclusion.

That very ugly/bold woman is my boss.

The battle zone/tank was near the village.

She brought eight/seven books to school.

The ancient pyramid/chariot belonged to a king.

The proud owner/baker loved to show off.

He attacked other/these children in the park.

These ivory/alien objects are odd discoveries.

Her extremely oily/limp hair needed washing.

The deep ocean/grave is his final resting place.

The silly rhyme/album amused the children.

She couldn't utter/alter what she was thinking.

The good nurse/candy made her feel much better.

You must wrap/fold the paper around the box.

Her glossy nylon/satin pants were bright red.

We thought that our city/side was doing well.

Their older/heavy brother wanted to lose weight.

The somber hymn/tomb made me feel sad.

The men in that squad/sport are often injured.

The broken zipper/button can't be repaired.

Those open/four windows are much too drafty.

The dirty-looking smog/soot was a dreary sight.

The annoying itch/beep bothered him.

His favorite aunt/pipe was his only comfort.

The old vulture/rooster was hungry.

He has only one year/life to live.

Her gentle eyes/face looked pretty today.

Please don't type/play while we're sleeping.

Those twin/bony girls suffer from malnutrition.

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