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Is word recognition different in central and peripheral vision?

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Abstract

Peripheral vision plays an important role in normal reading, but its role becomes larger for visually impaired people with central-field loss. This experiment studied whether lexical processing differs in central and peripheral vision through the analysis of word-frequency effects in lexical decisions. We asked two main questions: (1) Do central and peripheral vision differ in the time course of lexical processing? and (2) do central and peripheral vision differ in the quality of lexical processing? To address the first question, we examined the time course of frequency effects in central and peripheral vision over a range from 25 to 500 ms. We found that significant frequency effects occurred for the shortest exposures, 25–50 ms, in central vision, whereas significant frequency effects did not occur in peripheral vision until 100 ms. To address the second question, we used word-frequency effects as a marker for the nature of lexical processing. We compared frequency effects in central and peripheral vision for data within matched ranges of percent accuracy (0–20%, 20–40%, 40–60%, 60–80%, and 80–100%). We found that there was no difference in the pattern of frequency effects in central and peripheral vision at equivalent performance levels. We conclude that lexical processing is slower in peripheral vision, but the quality of lexical processing is similar in central and peripheral vision.

Keywords: Word recognition; Lexical processing; Peripheral vision; Central vision; Word-frequency effects; Low vision; Reading

1. Introduction

Central vision plays a fundamental role in reading. Studies have shown that when the letters at fixation were masked, reading rates declined drastically and the number of fixations increased (Fine & Rubin, 1999a; Rayner & Bertera, 1979; Rayner, Inhoff, Morrison, Slowiaczek, & Bertera, 1981). For example, in Rayner and Bertera (1979), masking the seven central letters on each fixation led to a reading rate less than 10 words/min. The importance of central vision in reading has also been demonstrated by Legge, Mansfield, and Chung (2001), who showed that the size of the visual span (the number of letters that can be recognized on a single fixation) was markedly reduced in peripheral vision (e.g., the visual span decreased from 10 letters in central vision to less than four letters at 10 deg in the lower visual field).

Parafoveal vision (analysis of information to the right or left of the fixated word) also plays an important role in normal reading. Studies using a moving window technique showed that reading was disrupted when the window size (the size of the visible text) was reduced to exclude the parafoveal information (McConkie & Rayner, 1975; Rayner & Bertera, 1979). Text up to 15 characters to the right of fixation has an impact on eye movements in normal reading (see Rayner, 1998, for an overview). Many people with low vision, however, must rely on peripheral vision to an extent that is rarely used for reading by people with normal vision.

Most people with low vision have difficulty with reading. Low vision is sometimes defined functionally as any visual impairment that results in the inability to read a newspaper at a normal distance even with the best refractive correction. More than three million people in the United States have low vision (Tielsch, Javitt, Coleman, Katz, & Sommer, 1995). The prevalence of low vision is higher in the older population because low vision often results from age-related eye diseases such as macular degeneration, cataract, glaucoma, or diabetic retinopathy.

The most common cause of low vision in developed countries is age-related macular degeneration, which often results in scotomas (blind spots) in central vision,

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termed *central-field loss*. People with central-field loss usually read very slowly (Faye, 1984; Legge, Rubin, Pelli, & Schleske, 1985; Whittaker & Lovie-Kitchin, 1993). Given that they must rely on peripheral vision for reading, some aspects of peripheral vision are likely to be critical to this slow reading. There are changes in eye movements when reading with peripheral vision, thus perhaps slow reading is due to poorer eye movement control with respect to processing information in peripheral vision. Studies of eye movements in people with central scotomas from macular disease have found that slower reading is associated with shortened saccades (Bullimore & Bailey, 1995; Rumney & Leat, 1994; Trauzettel-Klosinski, Teschner, Tornow, & Zrenner, 1994). Fine and Rubin (1999b) reported that, when visual impairments such as scotomas and cataracts were simulated for normally sighted participants, there was an increase in the number of saccades and in fixation duration, and a decrease in the size of saccades (see also Rayner & Bertera, 1979). But abnormalities other than eye movements must play a role because studies of reading in peripheral vision using RSVP, in which eye movements are minimized, still show slow reading (Chung, Mansfield, & Legge, 1998; Legge et al., 2001). These studies also show that reading is slow even when character size is enlarged to compensate for decreased spatial resolution.

It is of both theoretical and clinical importance to understand the factors limiting reading performance in peripheral vision. Pertinent differences could include increased lateral masking in peripheral vision (Bouma, 1970), decreased visual span (Legge et al., 2001), or decreased attentional resolution (He, Cavanagh, & Intriligator, 1996; Mackeben, 1999; Yeshurun & Carrasco, 1999). In this paper we ask whether inferior lexical processing is a contributing factor. In spite of its importance for understanding low-vision reading, the nature of lexical processing in peripheral vision has not been previously studied directly.

We focused on two questions. First, do central and peripheral vision differ in the time course of lexical processing? Differences might occur at the visual front-end: either slower neural processing, or the need for longer or additional fixations to encode visual information for reading. Legge et al. (2001) showed that the visual span decreases in peripheral vision, and requires longer exposure times to reach maximum values. Assuming that access to lexical information needs preliminary visual analysis for given inputs, it is possible that some type of early visual limitation in peripheral vision might delay lexical access.

The second question is whether lexical processing in central and peripheral vision differs qualitatively. Given the dominant and habitual role of central vision in normal reading, it is possible that specialized mechanisms develop through reading experience to handle fast and effective lexical access. For example, Pelli, Burns, Farell, and Moore (accepted pending minor revision) have shown that efficient recognition of individual characters in novel alphabets is learned quickly, but that the memory span for encoding of several characters in parallel develops much more slowly. It is possible that the latter capability depends on long-term reading experience in central vision. Further, Legge et al. (2001) considered the relationship between reading and letter recognition in central and peripheral vision. From a comparison of their human data with the performance of an ideal-observer model (Legge, Klitz, & Tjan, 1997), they proposed that different lexical-matching processes might be employed in human central and peripheral vision.

We consider two possibilities for the nature of lexical processing in peripheral vision. One possibility is that lexical processing is slower but is otherwise qualitatively similar to central vision. The other possibility is that lexical processing is both slower and qualitatively different in peripheral vision.

We examined the two possibilities using a lexical-decision task, in which participants make a judgment about whether a briefly presented letter string is a word or not. Specifically we asked how word-frequency influences the accuracy of lexical decisions at various exposure times in central and peripheral vision. It is well known that high-frequency words are processed more easily than low-frequency words in reading. Word-frequency effects (difference between high- and low-frequency words in performance) are ubiquitous in the empirical data from a variety of reading tasks which are sensitive to different aspects of lexical processing. These tasks include lexical decision (e.g., Monsell, Doyle, & Haggard, 1989; Seidenberg, Waters, Barnes, & Tanenhaus, 1984), semantic categorization (e.g., Balota & Chumbley, 1984; Monsell et al., 1989), naming (Balota & Chumbley, 1985; Monsell et al., 1989; Seidenberg et al., 1984), and normal reading (e.g., Henderson & Ferreira, 1990; Inhoff & Rayner, 1986; Just & Carpenter, 1980; Rayner & Duffy, 1986; see Rayner, 1995, 1998, Rayner & Pollatsek, 1989, for a review of frequency effects on eye fixation times in normal reading). Frequency effects have also been demonstrated in the simulation of computational models of reading (e.g., McClelland & Rumelhart, 1981; Reichle, Pollatsek, Fisher, & Rayner, 1998; Seidenberg & McClelland, 1989). Although theoretical views of frequency effects differ across researchers (see Monsell, 1991, for detailed discussion), it is clear that frequency effects provide an empirical marker for normal lexical processing in central vision. Thus we thought that the comparison of frequency effects in central and peripheral vision would provide a means for assessing the nature of lexical processing in peripheral vision. That is, if there is any difference in the lexical systems of central and peripheral vision, it may be reflected as different patterns of frequency effects. We compared frequency effects in central and peripheral vision in two ways—the dependence on stimulus exposure time (time course), and the magnitude of frequency effects at different levels of overall performance (i.e., for different ranges of accuracy in our lexical-decision task).

We made predictions as follows. First, if in peripheral vision lexical processing is slower but its nature is similar to that in central vision, there should be a difference in the time course of frequency effects: however, the pattern of frequency effects should not differ when accuracy levels are matched. Second, if peripheral vision is characterized by slower as well as poorer lexical processing relative to central vision, there should be a difference in the time course of frequency effects as well as in the pattern of frequency effects for matched levels of accuracy, factoring out differences in the time course of lexical processing.

2. Method

2.1. Participants

Twenty four students at the University of Minnesota participated in the experiment. The mean age of the participants was 20 with a range of 17–27. They were all native English speakers with normal vision. The mean acuity was 20/17 with a range of 20/12–20/23.

2.2. Apparatus

Visual stimuli were generated using a Cambridge Research System consisting of a 200 MHz PC (Dell Dimension XPS M200s) with a Visual Stimulus Generator graphics card (VSG 2/4-4 MB). Visual stimuli were displayed for the participants on a 21-inch monitor (Sony Trinitron MultiScan 20 se II) running at a frame rate of 160 Hz (640×480 pixel resolution). The PC was loaded with VSG software version 5.0 as well as custom software specially developed to run the experiment.

2.3. Materials and design

Four variables were manipulated in the experiment. First, stimuli were presented at fixation or 10 deg in the lower visual field. Three factors governed the selection of the location for peripheral testing: (1) Presentation of horizontal letter strings orthogonal to the vertical meridian produces less variation in retinal eccentricity of the letters than strings on the horizontal meridian (Petre, Hazel, Fine, & Rubin, 2000). (2) The eyes' optics remain good at 10 deg retinal eccentricity (Jennings & Charman, 1981). (3) Clinical opinion holds that the lower visual field is more suitable for reading than the upper visual field, supported by recent measurements of reading speed (Petre et al., 2000).

Second, stimuli were presented at six exposure times—25, 50, 100, 200, 350, and 500 ms. Third, stimuli were four or eight letters in length. Fourth, the frequency of words was high or low. For example, *rain*, *face*, *business* are high-frequency words, and *bail*, *mule*, *forensic* are low-frequency words. The mean frequencies of high- and low-frequency words were 115 (range 45–425) and 9 (range 6–13) per million respectively according to Francis and Kučera (1982). Frequency was also matched in four- and eight-letter words (means of 117 and 113, respectively, for high-frequency words; and 9 and 9 for low-frequency words).

Forty eight experimental conditions were generated in a factorial design-2 frequency $\times$ 2 eccentricity $\times$ 2 length $\times$ 6 exposures. All conditions were tested within participants. Letter size was 0.5 deg in central vision and 3.5 deg in peripheral vision. These values were 2.5 times larger than the critical print sizes (CPS) at each eccentricity reported in previous research (Chung et al., 1998). CPS is the smallest print size that yields maximum reading speed. Chung et al. showed that with letter sizes larger than CPS, reading performance was independent of print size.

Stimuli consisted of 576 words and 576 nonwords (matched in length). Nonwords were created by randomly shuffling the letters of words. For example, a nonword counterpart of a word target, *warn*, was *nwra*. [1] The experiment was composed of eight blocks (2 eccentricity $\times$ 2 frequency $\times$ 2 length). Each block included 72 words and 72 nonwords, with 12 words and 12

[1] The scrambling of letters in words to make nonwords could sometimes result in "wordlike" strings. The presence of such word-like strings could make the lexical-decision task more difficult. To analyze the impact of this factor, we examined whether bigrams and trigrams forming our nonwords all exist in the English lexicon (based on Francis & Kučera, 1982). A nonword was categorized as "wordlike" when all its component bigrams and trigrams exist in English (e.g., grue, teal, sile), whereas when a nonword contained any nonexistent bigram or trigram, it was categorized as "non-wordlike" (e.g., ahws, nwra). Of a total of 576 nonwords, 38 were word-like (31 in four letters and 7 in eight letters). When word-like and non-word-like strings were compared on accuracy and response latency with all other factors being collapsed, the mean accuracy of word-like strings was 6% lower than non-word-like ones, and the mean latency was 28 ms longer than for non-word-like strings. Thus the presence of word-like nonwords in 6.6% of the nonword trials, distributed across conditions, seemed to contribute to task difficulty. Of more interest was whether performance in central and peripheral vision was differently affected by nonword type. For this we compared the difference in accuracy between central and peripheral vision for non-word-like and word-like strings, respectively: for non-word-like strings, there was 11% and 57 ms difference between central and peripheral vision, and 8% and 52 ms difference for word-like strings. The magnitude of the difference was comparable across the two kinds of strings and there was no interaction between eccentricity and non-word-like vs. word-like strings ($F < 1$). Thus we consider it unlikely that this nonword factor had any significant impact on the major results reported in this paper.

nonwords assigned to each of the six exposures. Eccentricity and exposure were counterbalanced across participants, thus each participant saw each word only once. The presentation order of blocks and words within a block was randomized, with central and peripheral blocks interleaved (e.g., a central block followed by a peripheral block). Words were presented as black letters on a white background (40 cd/m^2) with a contrast of 99%.

2.4. Procedure

Each participant participated in the experiment for 1.5 h. Fig. 1 illustrates the sequence of events in a trial in central and peripheral vision. Vertical bars on the monitor created two gaps. These gaps were locations where target strings would appear in central and peripheral vision. The participant fixated the center of the upper gap. The lower gap was located at 10 deg below fixation. The participant initiated a trial by pressing the space bar, which was followed by a target string. The target string remained for a given exposure time and then was replaced by a mask for 100 ms. Participants were asked to respond as quickly as they could after the mask disappeared. They pressed one of two keys to indicate whether the target string was a word or not. Trials proceeded without feedback about the correctness of the response.

Participants were asked to maintain fixation throughout a trial. They were asked to report fixation errors whenever they failed in fixation. We emphasized the importance of maintaining good fixation. The mean percentage of fixation-error trials was 0.1% (error trials were excluded from analysis). In a control experiment, an eye tracker was used to monitor the fixation accuracy of two additional participants during the lexical decision task (see Section 2.5 below).

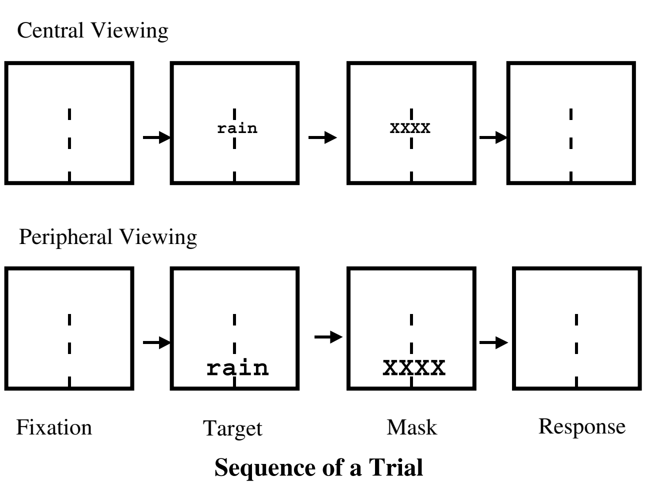

Fig. 1. The sequence of a trial. Upper picture: trial in central vision. Bottom picture: trial in peripheral vision.

Before a new block began, participants were informed about the location (upper or lower gap) and length (four- or eight-letters) of the targets. Participants were informed that the proportion of words and nonwords was similar. They were not informed about the manipulation of word frequency in the experiment.

2.5. Eye movement monitoring

We conducted a control experiment in which the eye positions of participants were monitored during the lexical-decision task. In the main experiment we relied on participants' reports to ensure that they fixated properly during the task. It is possible that participants involuntarily or unknowingly looked at the peripheral targets in a significant portion of the trials, thereby contaminating our findings.

In the control experiment, the eye movements of two, new participants were monitored with a video-based eye-tracker (ISCAN RK-726PCI PUPIL/CORNEAL REFLECTION TRACKING SYSTEM), which was interfaced with the computer. The eye tracker has accuracy typically better than 0.3 deg, and its signal was sampled every 16.7 ms by the computer (60 Hz). Viewing was binocular, with eye movements recorded from the right eye. Due to some limitations in the physical setup of the eye-tracker, only four-letter stimuli were tested and the letter size at 10 deg in the lower visual field was 2.6 deg. (This value, although smaller than the one used in the main experiment, was large enough to exceed the critical print size, 1.9 times larger than the critical print size at 10 deg eccentricity.) Viewing distance was 1 m. Other experimental conditions were identical to the main experiment. The eye tracker was synchronized to record eye position throughout the stimulus exposure in a trial.

3. Results

We were primarily interested in percent correct accuracy in the lexical-decision task, but we also recorded response latencies. We will first describe the accuracy results, then the latency results, and finally the eye-movement control experiment.

3.1. Accuracy

The accuracy of lexical decisions was computed in two ways: (1) percentage of correct responses for words (%correct for words), and (2) d', the index of discriminability between words and nonwords (d' was computed as the difference between the z-scores of hit and false alarm rates; hit rate is the proportion of correct responses to words—judging words as words, and false alarm rate is the proportion of incorrect responses to nonwords—judging nonwords as words). Both %correct and d' are presented in the graphs (Figs. 2–5). Because the two measures were overall consistent, we focus our discussion on %correct for simplicity.

Table 1 lists the significant main effects and interactions from a 2 (word frequency) × 2 (word length) × 2 (eccentricity) × 6 (exposure time) ANOVA. In the statistical reports, 1 indicates the results from %correct, and 2 indicates the results from d'. We now describe them in more detail.

Fig. 2 shows main effects of all four variables. Accuracy was lower overall for low-frequency words than high-frequency words (top), for eight-letter words than four-letter words (middle), and in peripheral vision than in central vision (bottom). In addition, accuracy increased with longer exposure times. These results are consistent with typical findings for the variables.

Fig. 3 shows the data broken down according to length, eccentricity, and exposure duration. First, there was an interaction between eccentricity and word length. The difference in accuracy between four- and eight-letter words was amplified in peripheral vision (dotted lines) compared with central vision (solid lines). This interaction is consistent with the idea that the reduced size of the visual span in peripheral vision makes it harder to recognize long words (Legge et al., 2001). In addition, there was an interaction between eccentricity and exposure time. Accuracy tended to reach a plateau faster (i.e., at shorter exposures) in central vision than peripheral vision. It led to a larger advantage in accuracy for trials with central stimuli early in the time course. The combination of the two interactions (eccentricity × exposure, eccentricity × length) produced necessarily a three-way interaction among eccentricity, exposure, and length.

Of key interest was whether the time course of frequency effects differed in central and peripheral vision. Frequency effects were measured as differences in accuracy between high- and low-frequency words. As seen in Fig. 4, frequency effects emerged more slowly in

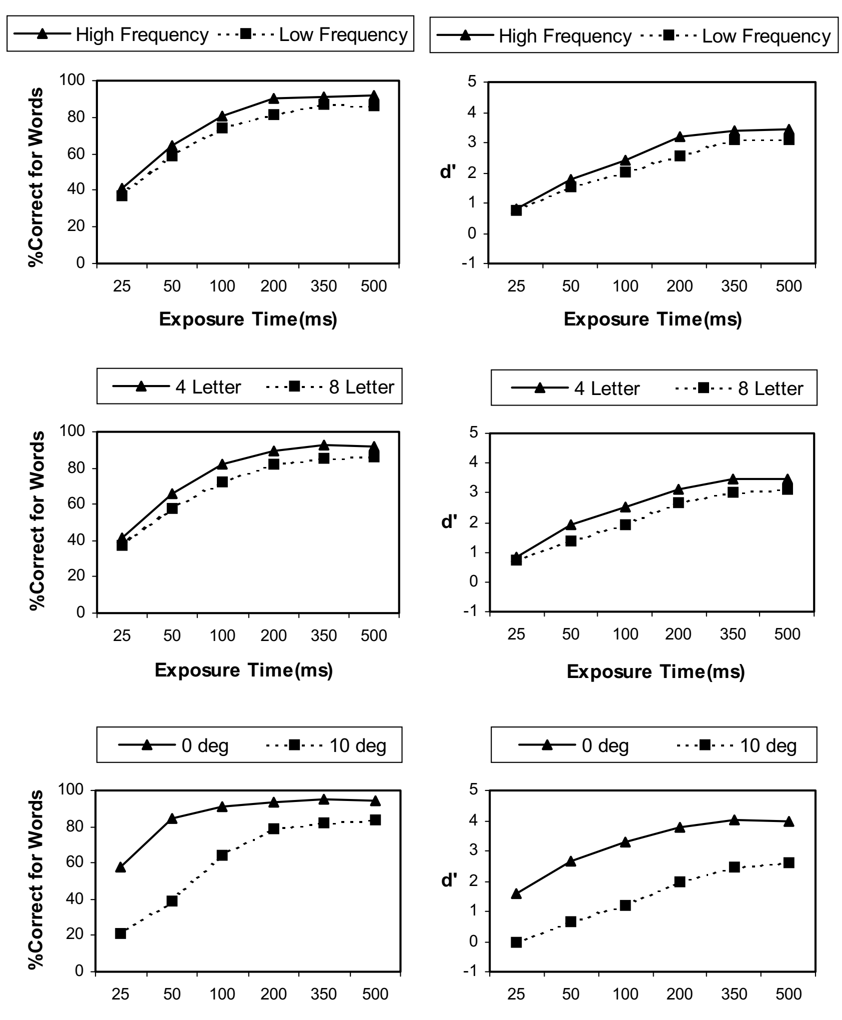

Fig. 2. Overall effects of word frequency, word length, eccentricity, and exposure time on lexical-decision accuracy.

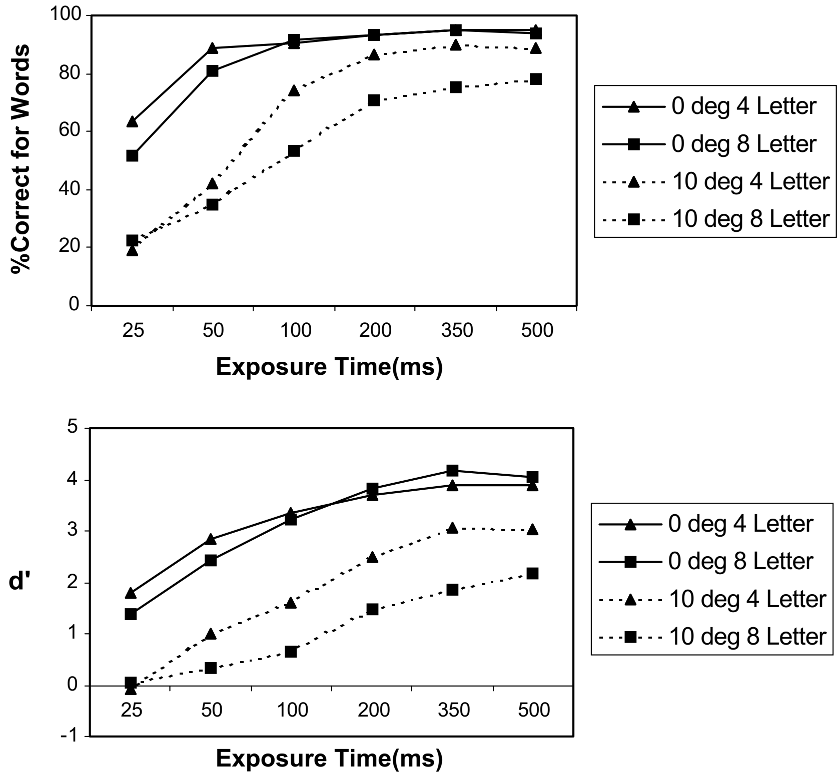

Fig. 3. Accuracy across exposure time as a function of eccentricity and length.

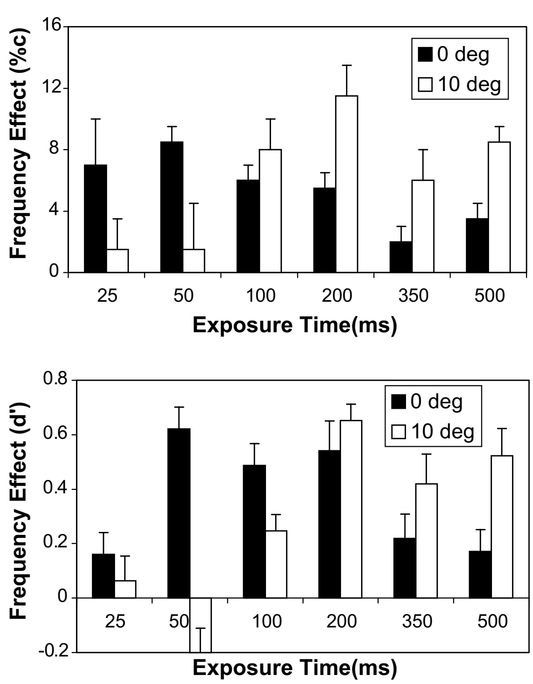

Fig. 4. The time course of frequency effects. Frequency effects were measured as the difference in accuracy between high- and low-frequency words. Error bars = 1 SE.

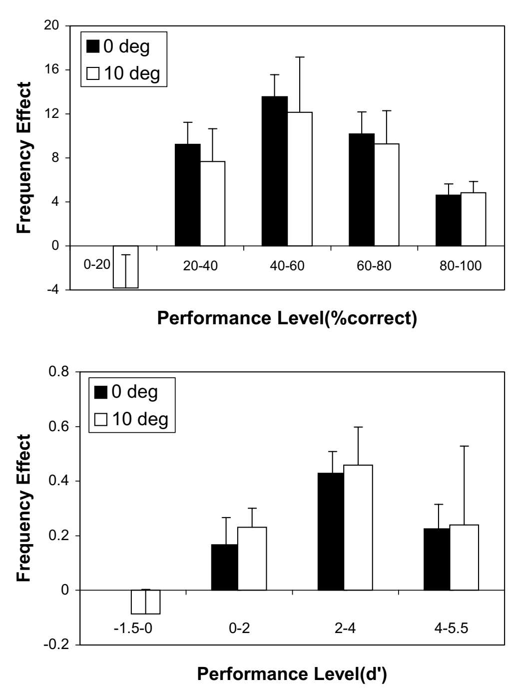

Fig. 5. The pattern of frequency effects across performance levels. Error bars = 1 SE.

peripheral vision. Significant frequency effects occurred for the shortest exposures in central vision, 25–50 ms, whereas significant frequency effects did not occur in peripheral vision until 100 ms. Table 2 shows *t*-test re-

Table 1
The significant main effects and interactions from a 2 (word frequency) × 2 (word length) × 2 (eccentricity) × 6 (exposure time) ANOVA

Effects	Statistic values
Word frequency	$F1(1,23) = 31.84$, $p < 0.001$; $F2(1,23) = 33.74$, $p < 0.001$
Word length	$F1(1,23) = 39.30$, $p < 0.001$; $F2(1,23) = 52.99$, $p < 0.001$
Eccentricity	$F1(1,23) = 133.48$, $p < 0.001$; $F2(1,23) = 224.06$, $p < 0.001$
Exposure	$F1(5,115) = 209.18$, $p < 0.001$; $F2(5,115) = 206.82$, $p < 0.001$
Eccentricity × length	$F1(1,23) = 23.24$, $p < 0.001$; $F2(1,23) = 34.63$, $p < 0.001$
Eccentricity × exposure	$F1(5,115) = 36.31$, $p < 0.001$; $F2(5,115) = 3.22$, $p < 0.01$
Eccentricity × exposure × length	$F1(5,115) = 17.49$, $p < 0.001$; $F2(5,115) = 10.22$, $p < 0.001$
Frequency × eccentricity × exposure	$F1(5,115) = 3.20$, $p = 0.01$; $F2(5,115) = 2.51$, $p < 0.05$

Note: No other effects were significant. $F1$: %correct. $F2$: d'.

Table 2
The results of *t*-tests on frequency effects

Exposure (ms)	*p*-values			
	Central vision		Peripheral vision	
	%correct	d'	%correct	d'
25	0.037	0.348	0.547	0.731
50	0.000	0.002	0.765	0.294
100	0.000	0.011	0.004	0.067
200	0.000	0.025	0.000	0.000
350	0.097	0.260	0.020	0.092
500	0.036	0.334	0.000	0.018

sults for the significance of frequency effects at all exposures: significance levels were slightly different for %correct and d', but both consistently show the later appearance of frequency effects in peripheral vision. The different time course of frequency effects in central and peripheral vision was also confirmed by the three-way interaction among frequency, eccentricity and exposure time on accuracy. These results indicate slower lexical processing in peripheral vision.

Interestingly, the pattern of frequency effects for shorter exposures (25–200 ms) in central vision was similar to the pattern of frequency effects for longer exposures (100–500 ms) in peripheral vision. The difference in time course between central and peripheral vision could not be characterized by a single time delay (i.e., linear shift on the time axis). A better characterization is to say that frequency effects took four times longer to emerge in peripheral vision (e.g., onset of the effect at 100 ms rather than 25 ms), although this multiplier overestimates the difference for the longest exposures.

Finally we conducted an analysis to determine whether the pattern of frequency effects differed in central and peripheral vision for matched levels of performance (accuracy). (Typically, this required comparing performance at longer exposure times in peripheral vision with performance at shorter exposures in central vision.) Fig. 5 shows frequency effects at five performance levels. We grouped the mean %correct and frequency effects from the 24 cells (2 eccentricity × 2 length × 6 exposures) into five levels based on ranges of accuracy. We grouped performance falling between 0–20% correct as performance level 0–20, performance falling between 20–40% correct as performance level 20–40, and so on up to performance falling between 80–100% correct as performance level 80–100. [2] In Fig. 5, the X-axis represents the five performance levels and the Y-axis represents the average frequency effects at each level (we averaged data across word length). The motivation for this analysis was to compare frequency effects in central and peripheral vision for trials yielding the same overall levels of performance independent of differences in time course. We assumed that if the quality of lexical processing in peripheral vision is similar to that in central vision, the pattern of frequency effects should be similar once sufficient time was allowed to reach equivalent levels of performance. However, if lexical processing is qualitatively different in peripheral vision, the pattern of frequency effects would not be similar even with sufficient time to compensate for differences in front-end visual analysis. Fig. 5 shows that the patterns of frequency effects were similar in central and peripheral vision across performance levels. This was confirmed by a null interaction between eccentricity and performance level in a two-way ANOVA (eccentricity × performance level) on frequency effects $[F1 < 1, F2 < 1]$. In addition, the main effects did not reach significance. (We excluded the lowest performance level from the analysis, because there were no data at this low performance level in central vision, see Fig. 5.) The results in Fig. 5 show that the lexical system in peripheral vision produces the same pattern of lexical effects given extra time to make up for slower visual analysis.

3.2. Latency

We examined the latency data to confirm that the results from the accuracy data were not related to a

[2] Even though half of the stimuli were words and half were nonwords, participants tended to respond "non-words" when they had low confidence about the stimuli. This accounts for performance levels below 50%.

Table 3
The response latency for correctly responded trials in lexical decisions

Duration (ms)	Central vision		Peripheral vision	
	HF	LF	HF	LF
A. Words				
25	668	671	701	671
50	609	638	753	715
100	607	618	705	714
200	617	630	690	713
350	680	689	753	776
500	767	778	857	892
B. Nonwords				
25	664		681	
50	651		694	
100	650		725	
200	657		748	
350	713		807	
500	800		888	

Note: Response latency was measured from the onset of stimuli until the participant's response. HF = high-frequency words. LF = low-frequency words.

speed-accuracy tradeoff. Table 3 shows the response latency for correctly responded trials in lexical decisions (latency was measured from the onset of stimuli until the participant's response). Overall the pattern of latency results was consistent with the accuracy pattern. First, peripheral vision showed longer latencies than central vision for both words and nonwords, indicating that lexical decisions are slower in peripheral vision [$F(1,23) = 20.44$, $p < 0.001$, for words; $F(1,23) = 11.49$, $p < 0.005$, for nonwords]. This is consistent with decreased accuracy in peripheral vision. Furthermore, for words, frequency effects (shorter latency for high-frequency words relative to low-frequency words) emerged more slowly in peripheral vision: while the first observation of the frequency effect was at 50 ms in central vision, it was after 100 ms in peripheral vision. This observation was supported by a three-way interaction among eccentricity, frequency, and exposure in an ANOVA on words [$F(5,115) = 3.34$, $p < 0.01$]. A similar three-way interaction was found from the accuracy data. [3]

In short, we found consistent patterns of results for latency and accuracy measures, confirming that the pattern of results in the accuracy data is not attributable to a speed-accuracy tradeoff.

3.3. Eye movement control experiment

In the control experiment, 1.2% of the trials were unusable due to loss of tracking. These trials were excluded from data analysis. Prior to examining eye movements, we examined the overall pattern of results in the lexical-decision task. Consistent with the results from the main experiment, there was an 8% benefit in accuracy in central vision over peripheral vision (92 vs. 84%), and an 8% benefit for high-frequency words over low-frequency words (92 vs. 84%). Frequency effects were 4, 9, 9, 9, 9, 5% at 25, 50, 100, 200, 350, 500 ms, respectively, in central vision, whereas in peripheral vision they were 0, 0, 13, 25, 8, 18%, consistent with a slower emergence of frequency effects in peripheral vision. In spite of some inevitable changes in the experimental setup, the data pattern from the control experiment was very consistent with that from the main experiment.

We compared the vertical eye positions for trials with stimuli in central vision and peripheral vision (10 deg lower visual field). We measured the eye positions from the onset of stimulus until its offset (i.e., during stimulus exposure). For trials with stimuli presented in central vision, all the eye positions fell into the range from −1.38 to 2.76 deg across the fixation point (i.e., 0 deg), with the mean eye position of 0.88 deg (SD = 0.72 deg). (The negative value indicates an eye position below the fixation point, and the positive value indicates an eye position above the fixation point.) For trials with stimuli in peripheral vision, all the eye positions fell into the range from −2.07 to 3.39 deg across the fixation point, with the mean eye position at 0.73 deg (SD = 1.02 deg).

Of key interest in eye monitoring was how accurately participants fixated during the lexical-decision task: in other words, how likely were they to look directly at the stimuli in peripheral vision? Given that stimuli were presented 10 deg below the fixation point in peripheral vision and that a maximum deviation of the eye from the fixation point in peripheral vision was 2.07 deg, we conclude that participants rarely, if ever, directly fixated the peripheral stimuli during testing. It appears, however, that eye fixations for trials with peripheral stimuli were slightly less accurate than for trials with stimuli in central vision, as indicated in a wider range of eye positions.

4. Discussion

The main results can be summarized as follows. First, significant word-frequency effects, measured as the difference in accuracy between high- and low-frequency words, occurred at the 25–50 ms exposures in central vision but not until 100 ms in peripheral vision, indicating that the time course of lexical processing is slower in peripheral vision. Second, the patterns of frequency effects were similar in central and peripheral vision when they were compared within matched levels of accuracy,

[3] Strangely, latencies were longer for high-frequency words than for low-frequency words at short durations (25–50 ms) in the periphery. However, these reversed frequency effects were not significant in *t*-tests [*ps* > 0.1].

indicating that the quality of lexical processing is similar in central and peripheral vision.

In our study, we used larger letters in peripheral vision than in central vision to compensate for differences in spatial resolution. In contrast, Rayner and Morrison (1981) examined lexical-decision performance for stimuli with fixed-size letters (three letters per degree) presented at fixation and up to 5 deg left or right of fixation. Not surprisingly, these authors found that performance on lexical decisions decreased rapidly in peripheral vision, dropping to chance at 5 deg. Presumably, this rapid decline in lexical-decision performance was due to decreased spatial resolution rather than inadequacies of post-visual lexical processing.

It is worthwhile to mention the possibility that lexical processing in peripheral vision may be similar in nature to lexical processing with stimulus degradation in central vision. Our data show main effects of word frequency and eccentricity but not the interaction of the two. Interestingly, several studies have reported analogous additive effects between word frequency and visual stimulus degradation in central vision. For example, Balota and Abrams (1995), and Borowsky and Besner (1993) examined the influence of word frequency and stimulus degradation in the lexical-decision task in which the stimulus was degraded by adding a noise mask to the letter string or by presenting the letter string at low luminance. They found main effects of frequency and stimulus degradation in response latencies but not their interaction, suggesting that word frequency and visual degradation might tap different stages of word processing, with visual degradation affecting an earlier and separate stage of information processing. The similarity between the processes of peripherally presented words and visually degraded words in central vision leads to the possibility that word recognition in peripheral vision can be explained consistently within the theoretical framework of word recognition in central vision.

In summary, we considered two possibilities for the nature of lexical processing in peripheral vision. One is that early visual limitations in peripheral vision might lead to a delay of lexical processing. The other is that if there is an interaction between early visual processes and higher-level language processes, the quality of lexical processing might be inferior in peripheral vision. We investigated these possibilities through the time-course and performance analyses of frequency effects in lexical decisions. We found that frequency effects emerged more slowly in peripheral vision, but that the pattern of frequency effects was similar in central and peripheral vision when performance was matched. From these findings, we conclude that central and peripheral vision differ in the speed but not in the quality of lexical processing.

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