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Psychophysics of reading. XVIII. The effect of print size on reading speed in normal peripheral vision

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Abstract

Reading in peripheral vision is slow and requires large print, posing substantial difficulty for patients with central scotomata. The purpose of this study was to evaluate the effect of print size on reading speed at different eccentricities in normal peripheral vision. We hypothesized that reading speeds should remain invariant with eccentricity, as long as the print is appropriately scaled in size—the scaling hypothesis. The scaling hypothesis predicts that log–log plots of reading speed versus print size exhibit the same shape at all eccentricities, but shift along the print-size axis. Six normal observers read aloud single sentences (~ 11 words in length) presented on a computer monitor, one word at a time, using rapid serial visual presentation (RSVP). We measured reading speeds (based on RSVP exposure durations yielding 80% correct) for eight print sizes at each of six retinal eccentricities, from 0 (foveal) to 20 deg in the inferior visual field. Consistent with the scaling hypothesis, plots of reading speed versus print size had the same shape at different eccentricities: reading speed increased with print size, up to a critical print size and was then constant at a maximum reading speed for larger print sizes. Also consistent with the scaling hypothesis, the plots shifted horizontally such that average values of the critical print size increased from 0.16 deg (fovea) to 2.22 deg (20 deg peripheral). Inconsistent with the scaling hypothesis, the plots also exhibited vertical shifts so that average values of the maximum reading speed decreased from 807 w.p.m. (fovea) to 135 w.p.m. (20 deg peripheral). Because the maximum reading speed is not invariant with eccentricity even when the print size was scaled, we reject the scaling hypothesis and conclude that print size is *not* the only factor limiting maximum reading speed in normal peripheral vision. © 1998 Elsevier Science Ltd. All rights reserved.

Keywords: Low vision; Peripheral vision; Reading

1. Introduction

Reading is critical to full participation in modern society. For more than three million people in the United States who suffer from impaired vision [1] and who are classified as having low vision, reading presents a major challenge for daily living. Indeed, low vision can be functionally defined as the inability to read the newspaper, with the best refractive correction, at a normal reading distance of 40 cm [2–4].

In developed countries, the leading cause of visual impairment is age-related maculopathy, a degenerative disorder that can progressively affect the macular region of the retina, often culminating in an irreversible central scotoma. People with central scotomata must use peripheral vision to read, which has been shown to be a slow and inefficient process in both clinical and research settings [2,4–6]. The prevalence of age-related maculopathy in the United States, derived from two large-scaled epidemiological studies, was ~ 11–14% for population of age 60–74 years, and ~ 28% for population over the age of 70 [7,8]. Among these populations, approximately 10–20% will eventually develop the exudative form of age-related maculopathy, which is responsible for an estimated 1.2 million cases of severe visual loss [9]. The understanding of why reading is slower in the peripheral visual field is important in the visual rehabilitation of this group of low vision patients.

One possible explanation for slow reading in peripheral vision is related to problems with oculomotor control. These problems, including increased saccadic latency and undershooting of saccades, have been

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found in people who use their peripheral vision because of naturally occurring or simulated central scotomata [10–12]. Eye movements certainly affect reading speed, as demonstrated by an increase in reading speed in normal observers for a reading task that minimizes the need for eye movements [13]. In this reading task, termed 'rapid serial visual presentation' (RSVP), text is presented one word at a time for a given duration at the same screen location (e.g. [13–18]). If reading is poor in the periphery because of deficient eye-movement control, then RSVP should be more beneficial to peripheral than central vision. The improvement in reading speed using RSVP over conventional page reading should be larger in peripheral than central vision. Inconsistent with this prediction, the improvement in reading speed using RSVP over conventional page reading was a factor of 1.5 for people with central scotomata who read with their peripheral vision, compared with a factor of 2.1 for people with intact central fields [16,17]. The smaller improvement in reading speed in peripheral vision, when eye-movement control is factored out, suggests that oculomotor control cannot account fully for the slow reading speed associated with peripheral vision.

Another explanation that may account for the slower reading speed in peripheral vision is the differences between rod- and cone-mediated vision. Compared with the central retina, the peripheral retina is dominated by rod-photoreceptors which have different spatio-temporal properties than cone-photoreceptors, such as poorer spatial resolution. By comparing reading speeds using targets that are equated in detectabilities for cones and rods, Chaparro and Young [19] found that rod-mediated reading is still slower than cone-mediated reading. This finding suggests that the difference in reading speed between central and peripheral vision cannot be accounted for by the difference in visual sensitivity of the cone and rod visual system, because the targets were equally detectable by either type of photoreceptors. Thus, the intrinsic differences between cones and rods is unlikely to be a factor accounting for the slow reading speed in peripheral vision.

The third possible factor that may account for the slow reading in peripheral vision relates to the fact that the convergence of cone-photoreceptors upon one ganglion cell increases in the periphery. This explains why similar visual performance can be obtained at different retinal eccentricities for some spatial tasks when stimuli are scaled in size to equate the coverage of ganglion cells. The classical example is the spatial contrast sensitivity function, which remains shape-invariant at various retinal eccentricities as long as the stimulus size is scaled appropriately [20,21].

Given the importance of scaling laws of this kind for understanding peripheral vision, one important question that arises is whether reading performance can be equated by scaling print size in peripheral vision. In central vision, it is well known that reading speed depends on print size: reading speed increases with print size up to a *critical print size* beyond which reading speed remains at a plateau level, termed the *maximum reading speed* [3,22–25]. For extremely large print (characters subtending more than 3 deg), reading speed declines [3,4,6,13,22,26]. Empirically, the studies of Rubin and Turano [16] and Latham and Whitaker [27] both suggest that the maximum reading speed attainable in peripheral vision is lower than that in the fovea. Clinically, our experience also indicates that very often, magnification of print cannot restore the normal maximum reading speed in patients with central visual field defects. As yet, however, there has been no systematic investigation of how reading speed varies as a function of print size in peripheral vision. In addition, existing data in the literature are insufficient to determine how properties of reading, especially the critical print size and the maximum reading speed, change as a function of retinal eccentricity.

The purpose of this study, therefore, was to measure the effect of print size on reading speed at different retinal eccentricities in normal peripheral vision. By print size, we refer to the angular subtense of the print on the retina, not the physical print size on the page. Although our measurements were collected from observers with normal vision, it is likely that our findings identify limitations on the reading performance that could also affect people with central visual field defects. In addition, the results of the present study provide a 'normal standard' to which data from patients with central field defects can be compared.

We examined the role of print size in central and peripheral vision by studying our null hypothesis, the scaling hypothesis, as illustrated in Fig. 1. According to this hypothesis, reading performance in peripheral vision is the same as in central vision, except for a scaling factor in print size. This scaling is represented by a horizontal shift of the plot along the print-size axis (i.e. the abscissa). The scaling hypothesis predicts that (1) the critical print size increases in peripheral vision; (2) the reading speed versus print size plot is shape-invariant in peripheral vision and (3) the maximum reading speeds attainable in central and peripheral vision are identical.

To test the scaling hypothesis, we measured reading speeds at several retinal eccentricities. We used the RSVP paradigm to minimize limitations due to eye movements. At each eccentricity, we constructed plots of reading speed versus print size, from which the critical print size and the maximum reading speed were derived. We used meaningful sentences as our text materials because they are more representative of natural reading than strings of random words.

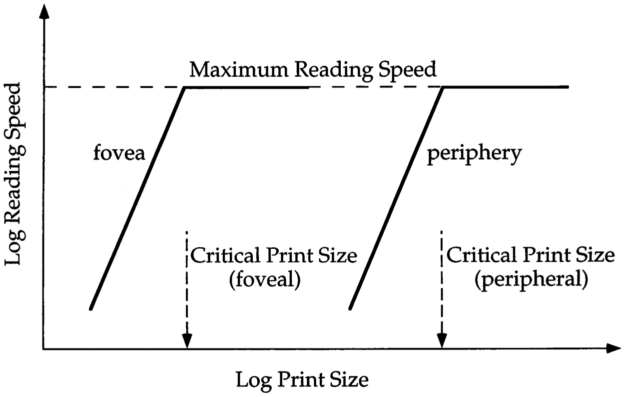

Fig. 1. A schematic diagram illustrating the 'scaling hypothesis'. When reading speed is plotted as a function of print size on log–log coordinates, we expect that reading speed will first increase with print size, up to the critical print size, and then plateau at the maximum reading speed. The scaling hypothesis predicts that in peripheral vision, the plot of reading speed versus print size will shift horizontally toward larger print size. Accordingly, the critical print size will increase in size in peripheral vision, but that the plot of reading speed versus print size will remain shape-invariant and that the maximum reading speed will stay at the same asymptotic level.

Recently, inconsistent results have been reported regarding the capacity of peripheral vision to take advantage of contextual cues present in meaningful sentences. Latham and Whitaker [27] found that for their two normal observers, sentences were read at about the same speed as random words in peripheral vision. This suggests that peripheral vision does not benefit from contextual cues. Contrary to this finding, Bullimore and Bailey [12] and Fine and Peli [28] have shown that observers with central visual field defects read sentences faster than random words. This indicates that contextual cues are helpful in peripheral vision. In light of these inconsistent findings, we have compared reading speeds for meaningful sentences versus random words at various eccentricities in a second experiment.

2. Methods

2.1. Stimuli

We measured oral reading speeds using single sentences. Sentences were extracted from nine novels obtained from Project Gutenberg via the world-wide web[1] (see appendix for a list of the novels). The sentences were selected to have lengths, including spaces, between 40 and 80 characters (mean = 53.2 ± 8.0), and to only contain words from the 5000 most frequent words in written English, according to word-frequency tables derived from the British National Corpus[2] (see [29]). Only sentences were used that contained no punctuation other than a period. No semantic or syntactic criteria were used in selecting sentences. This method generated 2630 sentences with eight to 14 words (mean = 11 ± 1.7 words). The total number of unique words used in our pool of sentences was 2219. The period at the end of each sentence was removed. When applicable, words were replaced by their American-spelling counterparts, e.g. we used the word 'color' instead of 'colour'.

For each trial, one sentence was chosen randomly from the pool of sentences. None of the observers read any sentence more than once. We presented the sentences using the RSVP paradigm, i.e. words of a sentence were presented sequentially, one word at a time, at the same location on the display for a fixed exposure duration. There was no blank frame (inter-stimulus interval) between each pair of words. Words were rendered in Times-Roman font, a proportionally spaced font, and were presented as high-contrast (ca. 90%), black letters on a white background of 110 cd/m^2. These text stimuli were generated and presented using an Indy workstation (Silicon Graphics Inc.) and a Sony color graphics display monitor (Model # GDM-17E11, refresh rate = 75 Hz). The temporal dynamics of the computer and the monitor were verified using a photodetector and an oscilloscope.

We measured reading speed for eight print sizes in central vision and at retinal eccentricities of 2.5, 5, 10, 15 and 20 deg in the lower visual field. The print sizes used were different for the various eccentricities, but the range of print size always spanned ~0.7 log units. We defined print size as the visual angle in degrees subtended by a lower-case 'x'. At a viewing distance of 40 cm, each pixel on the monitor screen subtends an angle of 1.98 arc min. This resolution is fine enough for peripheral testing, but not for foveal and parafoveal testing. Thus, we used viewing distances of 200 cm and 120 cm for testing at the fovea and 2.5 deg eccentricity, respectively. For the smallest print size that we used, each pixel subtended an angle of 23.7 arc s.

We used the lower visual field as the retinal locus for peripheral vision testing because the local variation in eccentricity of letters within a word is much smaller than when the word is presented in the left or right visual fields. For instance, at a retinal eccentricity of 15 deg, a 14-letter word of print size 1.6 deg (large enough to attain maximum reading speed, see Section 3 below) presented in the inferior/superior visual field will have the first and the last letter positioned at a radial eccentricity of ~18.7 deg. This means that the local variation in eccentricity of letters within the word is about 3.7 deg. In contrast, if the word is presented along the horizontal meridian in the left or the right visual field, then the local variation in eccentricity will be ~22.4 deg (14 × 1.6 deg)! In addition, the lower visual field is

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[1] URL:http://promo.net/pg

[2] The British National Corpus comprises of over 80 million words of written English. Details can be obtained at http://info.ox.ac.uk/bnc

the region commonly used in studies examining peripheral vision (e.g. [19,27,30]). Consequently, the use of the inferior visual field will facilitate comparison of our data with those in the literature. Recent research indicates that people with central scotomata resulting from juvenile forms of macular degeneration often place text below their scotoma to read, thus using their lower visual fields [31], but this may be less true of people with age-related maculopathy [32]. Nevertheless, evidence from a study with simulated central scotomata suggests that the inferior visual field supports faster reading speeds than superior, nasal or temporal fields [33].

2.2. Procedure

We defined our criterion reading speed as the RSVP exposure time that yields 80% of words identified correctly, estimated from a psychometric function for a particular condition (i.e. eccentricity x print size). Psychometric functions were constructed based on the proportion of words read correctly at six different RSVP exposure durations that were used for any particular condition. The range of exposure duration, typically spanning one log unit, was determined during the practice sessions. Each condition was tested twice, on different days. Data were pooled across the two sessions so as to compute the proportion of words read correctly for that particular condition. A word was scored as being read correctly as long as the observer said the word correctly, irrespective of its word order within the sentence. Each eccentricity x print size psychometric function was based on a total of 36 sentences (six sentences at each of six durations), with the total number of words read ranging from 52 to 78 (mean = 65.9 ± 4.2). The order of testing the six retinal eccentricities was counter-balanced across the six observers according to a Latin-Square design.

We fitted the psychometric functions using a cumulative Gaussian curve. To obtain the criterion reading speed, we derived from the best-fitting psychometric function the exposure duration that yields 80% of the words read correctly, and then converted the duration into speed according to the following equation:

$$\left[\text{Reading speed (w.p.m.)} = \frac{60}{\text{RSVP word exposure duration (s)}}\right]$$

Note that our use of an 80%-correct reading accuracy means that an observer with a reading speed of 100 w.p.m. actually only got 80 words correct in one min when exposed to a text-presentation speed of 100 w.p.m. Some other methods of calculating reading speed take into account the number of errors made, and for those cases, the reading speed for the same observer would come out to be 80 w.p.m.

2.3. Eye-movement monitoring

To ensure that the observers fixated properly so that the text was presented at the intended retinal eccentricity, we monitored the observers' fixation using a video-based eye-tracker (ISCAN RK-416, Boston, MA). A long, red horizontal line was drawn on the monitor to guide the observers' fixation, and text was presented underneath this line at a distance corresponding to the testing eccentricity (except for testing central vision when the fixation line was not presented and observers could look directly at the text). Based on our pilot study and the study of Rubin and Turano [16], we used a long line to control fixation instead of a single dot, because of the possibility that observers might make intra-word saccades when reading words that are long and large in size. We instructed the observers to 'look at the red line' throughout the trial and not to move their eyes away from the red line. The observers could choose either to fixate steadily any point along the fixation line, or to move their eyes horizontally along the line while they read. Prior to the beginning of each trial, i.e. each sentence, the observer was asked to fixate the fixation line for calibration purposes. The vertical eye position was then sampled at 60 Hz for 1 s. The average of these sampled eye positions was taken as the calibrated vertical eye position for the trial. As soon as this calibration process was completed, the observer initiated the trial and the vertical eye position at any instant was compared with the calibrated eye position, using a customized program that ran on an IBM AT computer. Whenever the eye position drifted below the calibrated eye position by two standard deviations of normal fixation, as determined prior to the study, the computer generated an audio sound which acted as a warning to the observer. At the end of a trial, the proportion of eye-position samples that exceeded two standard deviations from the calibrated eye position was calculated. Trials in which the proportion of such eye-positions exceeded 5% of the total number of eye-position samples were discarded. Approximately 15–20% of trials were discarded and repeated.

2.4. Observers

Six college-age observers with normal vision participated in this study. All had (corrected) acuity of 20/20 or better in both eyes (range: 20/13 to 20/20). Acuities were measured using the ETDRS charts, with credit given to each letter that was read correctly. To avoid potential optical aberrations from looking off-axis through spectacle corrections, all the observers recruited were either emmetropic, or wore contact lenses to correct for their refractive errors. None of our contact-lens wearing observers had astigmatism that required correction using toric lenses, which might also introduce aberrations in the inferior visual fields because of the design of the lenses. Written informed consent was obtained from each observer after the procedures of the experiment were explained, and before the commencement of data collection. None of the observers had prior experience in reading in peripheral vision or with the RSVP paradigm. The first two experimental sessions were used for practice. Our protocol of testing each condition in two separate sessions, combined with the Latin-Square design, minimized the influence of any residual practice effects.

2.5. Sentences versus random words

To determine whether our findings can be generalized to reading of random words, which lack contextual cues, we compared maximum reading speeds for random words with those for meaningful sentences in two of the six observers who participated in the main experiment (observers AW and PL). Maximum reading speeds were determined using similar procedures as in the main experiment, for retinal eccentricities of 0 (foveal), 5, 10 and 15 deg in the inferior visual fields. Print size used was twice as large as the critical print size for the respective eccentricity, as determined in the main experiment. Sequences of random words were generated by scrambling the word order within sentences randomly selected from the same pool of sentences used in the main experiment. As before, a word was scored as being read correctly if the observer said the word correctly, irrespective of its word order within the sequence. In each block of trials, either meaningful sentences or random-word sequences were presented. The order of testing of these two types of text was counter-balanced across the four eccentricities and between the two observers.

3. Results

To derive reading speeds, we plotted psychometric functions of the proportion of words read correctly as a function of the RSVP exposure duration. Fig. 2 shows eight of these functions, one for each of eight print sizes, obtained from one observer at a retinal eccentricity of 5 deg. Each solid curve represents a cumulative Gaussian fitted to the data obtained for one print size. Reading speed is defined using the criterion exposure duration that yields 80% of the total number of words read correctly. The effect of using other criteria on the results will be discussed later.

In Fig. 3, reading speeds are plotted as a function of print size, with retinal eccentricity as the parameter. Each panel presents data for one observer. At all eccentricities, reading speeds rise with increasing print size until a plateau is reached. We fitted two straight lines (on log–log coordinates) to each set of reading speed versus print size data, with the slope of the second line fixed as zero [3,24]. We will refer to this curve-fitting as the two-line fit. The intersection of the two lines represents the point at which reading speed becomes independent of print size. We refer to this point as the critical print size. In general, the critical print size becomes progressively larger as the retinal eccentricity increases (repeated measures ANOVA: $F_{(df=5,25)} = 109.0$, $P < 0.0001$), indicating that larger print is required in peripheral than central vision in order to attain the maximum reading speed. This finding is consistent with the first prediction of the scaling hypothesis.

The second prediction of the scaling hypothesis is that plots of reading speed versus print size are shape invariant in central and peripheral vision. Because we fixed the slope of the upper limb of the two-line fits to be zero, the shape of the plot is then governed by the slope of the rising limb. Pooled across the six observers, there is no significant effect of eccentricity on the slope of the rising limbs, consistent with shape invariance in central and peripheral vision (repeated measures ANOVA: $F_{(df=5,25)} = 0.653$, $P = 0.662$). The mean value (± 1 S.E.M.) of these slopes is 2.32 ± 0.18 log (w.p.m.)/log (deg), suggesting a sharp rise of reading speed with print size.

The third prediction of the scaling hypothesis is that maximum reading speeds are the same in central and peripheral vision (i.e. identical plateau levels in the curves of speed versus print size). Fig. 3 shows clearly that this is not the case. Besides horizontal shifts along the print-size axes, plots of reading speed versus print size obtained for various eccentricities also demonstrate vertical downward shifts along the reading-speed axes. The progressive downward shift of the plots along the reading-speed axes indicates that the maximum reading speed decreases systematically as retinal eccentricity increases (repeated measures ANOVA: $F_{(df=5,25)} = 104.6$, $P < 0.0001$).

To ascertain that our findings regarding the scaling hypothesis are not unique to the two-line fit that we adopted, we also fitted our data using the curve-fitting procedure used by Latham and Whitaker [27]. Three parameters are specified in this curve-fitting procedure: (1) the maximum reading speed; (2) the 'critical character size', defined as the print size corresponding to half the maximum reading speed and (3) 'reading acuity', defined as the print size that gives a reading speed of 0 w.p.m. Because this procedure does not readily provide a parameter to describe the shape of the reading plots, we adopted the ratio of the 'critical character size' and 'reading acuity' as a representation of the shape of the

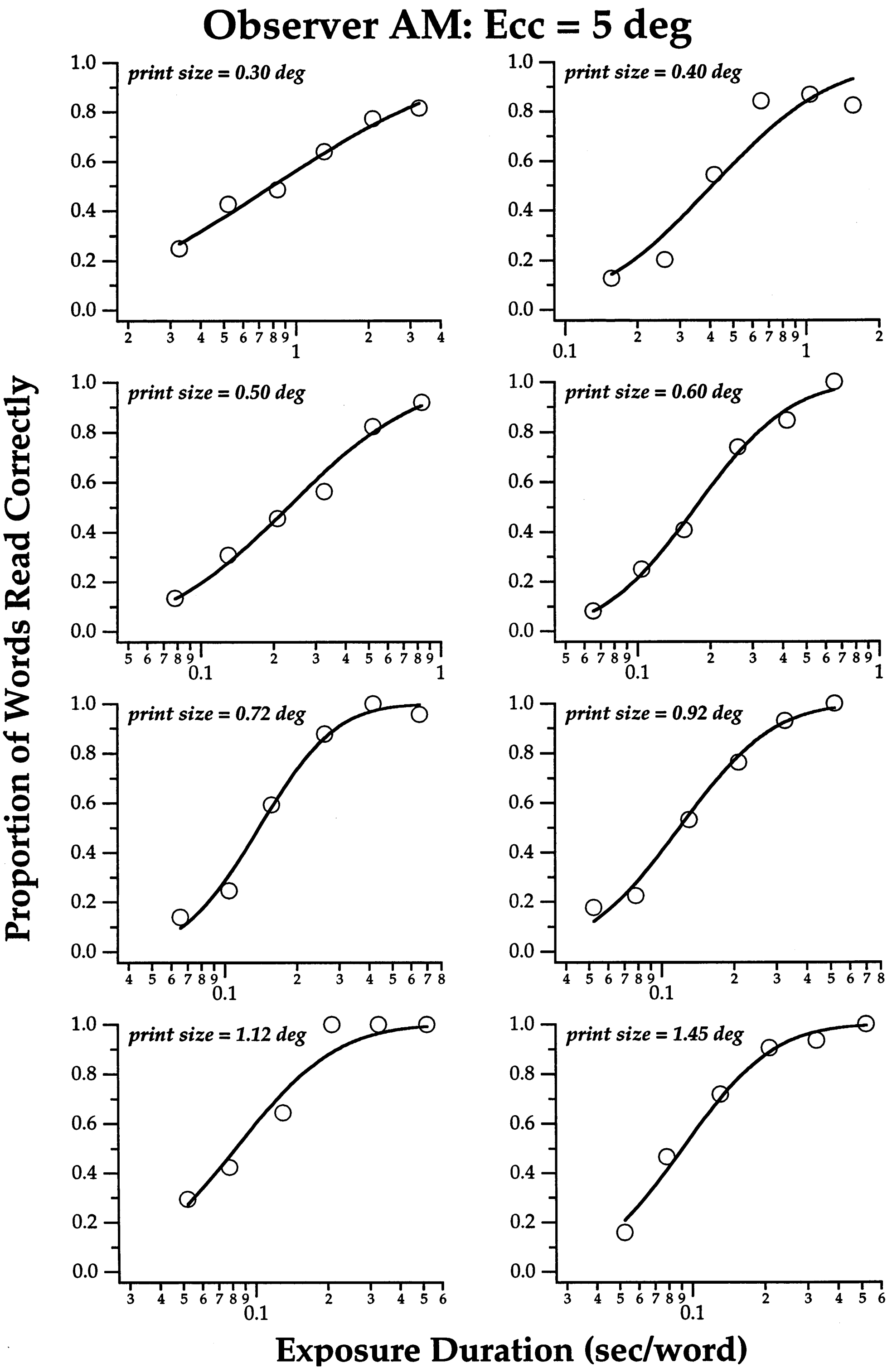

Fig. 2. Proportion of words read correctly is plotted as a function of exposure duration (s/word) for eight print sizes (0.3–1.45 deg) read by observer AM at a retinal eccentricity of 5 deg. Each panel presents data for one print size, given in the upper left hand corner. For each print size, six RSVP word exposure durations were tested and a cumulative Gaussian function was used to fit the psychometric function. From each psychometric function, we derived the criterion reading speed using the RSVP word exposure duration that gives 80% of the proportion of words read correctly. Note that the slope of the psychometric function is flatter for the small than the large print, and that the slopes are very similar for the few largest print sizes.

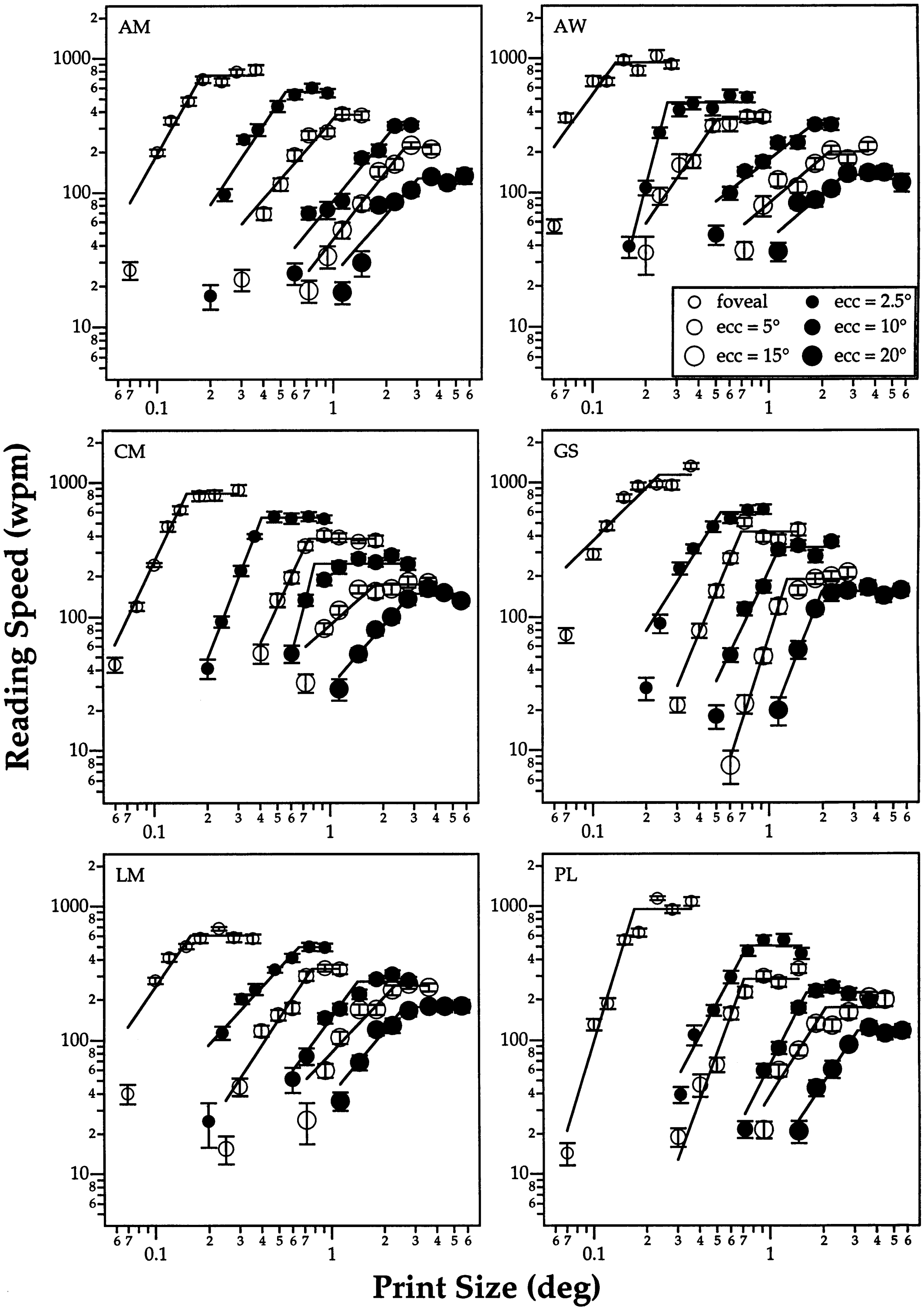

Fig. 3. Reading speed (w.p.m.) is plotted as a function of print size (deg), with retinal eccentricity as the parameter. Each panel presents data obtained from one observer. In each panel, the six plots represent data obtained at, from left to right, the fovea, 2.5, 5, 10, 15 and 20 deg eccentricity, respectively. Each plot was fitted with the two-line fit as described in the text. Error bars represent ± 1 S.E. of estimate of the reading speed at the 80%-correct level, derived by using a Monte Carlo simulation.

plots. Despite the differences in the parameters of these fits, the general conclusions remain unchanged: the critical character size increases with eccentricity (repeated measures ANOVA: $F_{(df=5,25)} = 4.11$, $P = 0.007$); the shape of the reading plots remain unchanged in peripheral vision (repeated measures ANOVA:

$F_{(df=5,25)} = 0.975$, $P = 0.452$) and the maximum reading speed decreases as a function of eccentricity (repeated measures ANOVA: $F_{(df=5,25)} = 15.06$, $P < 0.0001$).

3.1. E_2 for critical print size and maximum reading speed

Fig. 4 summarizes the critical print sizes and the RSVP exposure durations that correspond to the maximum reading speeds as a function of retinal eccentricity. We fitted each set of data with a regression line of the following form [34]:

$$\left[T = T_0 * \left(1 + \frac{Ecc}{E_2}\right)\right]$$

where T represents either the critical print size or the RSVP exposure duration corresponding to the maximum reading speed, T_0 is either the critical print size or the RSVP exposure duration obtained at the fovea, Ecc is the eccentricity on the x-axis and E_2 is the eccentricity at which the value of the y-variable is twice the foveal value. The E_2 parameter is commonly used to represent the rate of change of the variable of interest as a function of eccentricity [34–38]. A high E_2 value implies that the variable of interest changes slowly with eccentricity whereas a low E_2 value implies that the variable changes quickly with eccentricity. The value of E_2 for critical print size is 1.39 ± 0.75 deg and that for exposure duration at maximum reading speed is 4.13 ± 0.78 deg.

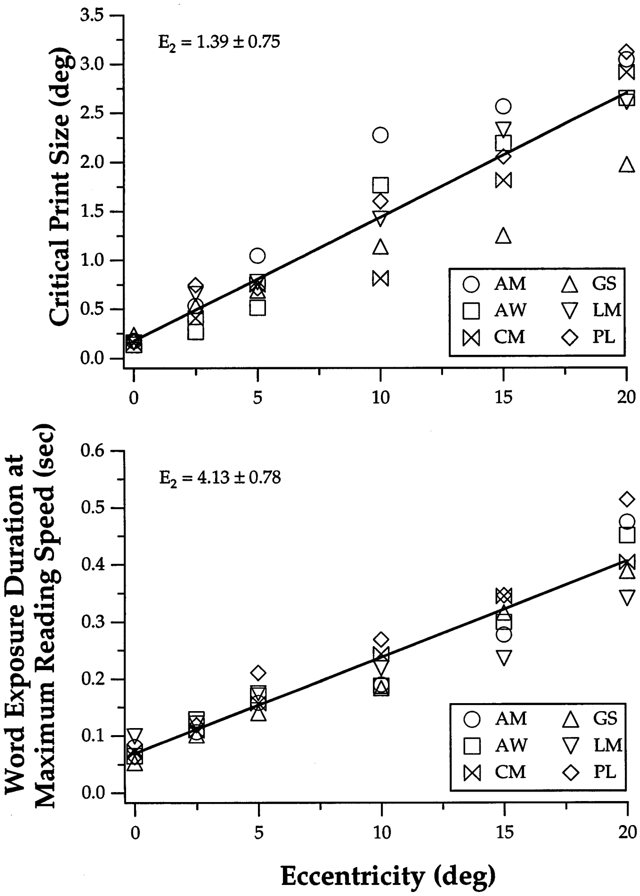

Fig. 4. The change of critical print size (top) and word exposure duration corresponding to maximum reading speed (bottom) as a function of eccentricity (deg) are plotted for the six observers. The solid lines are the best-fitting regression line from which the E_2 factors are derived (see text for details). Different symbols represent data obtained from different observers.

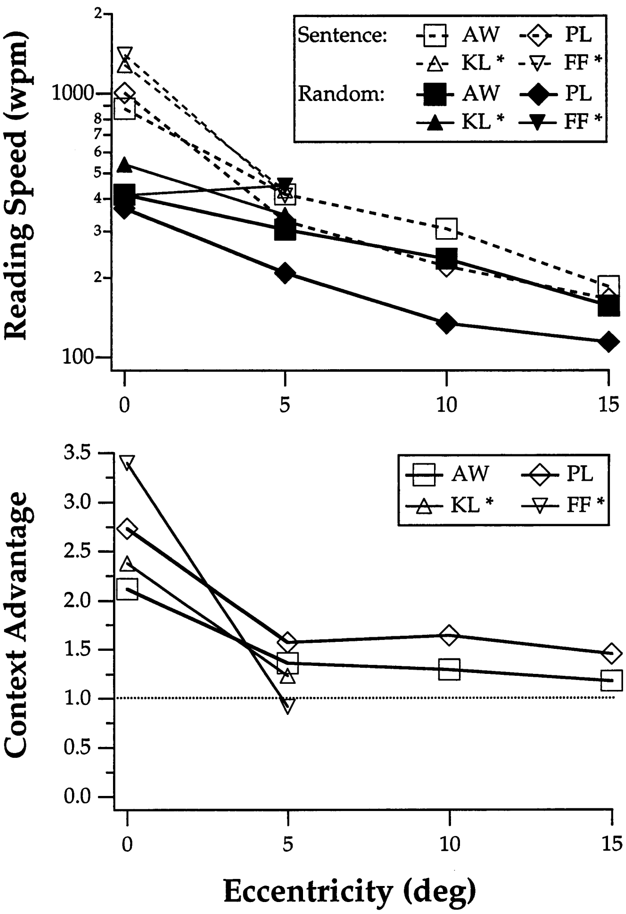

Fig. 5. Reading speed (w.p.m.) is plotted as a function of eccentricity (deg) in the top panel, where reading speeds for sentences and random-word sequences are compared for the two observers who participated in the present study (AW and PL) and the two observers who participated in the study of Latham and Whitaker [27] (KL and FF: demarcated by asterisks). The ratio of reading speeds for sentences and random words, representing the context advantage, is plotted as a function of eccentricity in the bottom panel. Ratios greater than one implies faster reading speed for sentences than for random words.

3.2. Sentences versus random-words

Reading speeds obtained for meaningful sentences and random-word sequences are plotted as a function of retinal eccentricity for two observers in Fig. 5 (top panel: square and diamond symbols). Triangular symbols are data replotted from the study of Latham and

Whitaker [27] for a later comparison (see Section 4). The advantage of reading meaningful sentences over random words, expressed as the ratio of the reading speeds for the two types of text, is shown in the bottom panel. For both observers, reading speeds were clearly higher for meaningful sentences than for random-word sequences at all eccentricities; however, the advantage of reading meaningful sentences over random words is not identical at all eccentricities (repeated measures ANOVA for the interaction of eccentricity and type of text: $F_{(df=3,3)} = 35.9$, $P = 0.008$). Specifically, the advantage is the biggest at the fovea, and diminishes as retinal eccentricity increases. Averaged between the two observers, the ratio decreases from 2.43 at the fovea to 1.32 at 15 deg eccentricity. For these data, the E_2 factors for reading speed for sentences and random words are 3.59 and 7.36 deg, respectively. The almost two-fold difference in E_2 indicates that reading speed changes slower with eccentricity for random words than it does for sentences.

3.3. Criterion effect

Fig. 2 shows that the slope of the psychometric function obtained for the smallest print size is flatter than the rest of the psychometric functions. Because we defined reading speeds as the points corresponding to 80%-correct on the psychometric functions, unless the psychometric functions have the same shape at all print sizes and eccentricities, our results might depend on the choice of criterion. Fig. 6 plots the slopes of psychometric functions versus print size, expressed as multiples of the observers' critical print size. Slopes are plotted for all observers at all eccentricities and print sizes. Clearly, the slopes of the psychometric functions are not constant at all print sizes. In particular, for print sizes smaller than the critical print size (i.e. print sizes smaller than 1.0 in Fig. 6), the slopes of the psychometric functions become progressively shallower as the print size diminishes. For print sizes larger than the critical print size (i.e. print sizes larger than 1.0 in Fig. 6), the slopes are more or less similar.

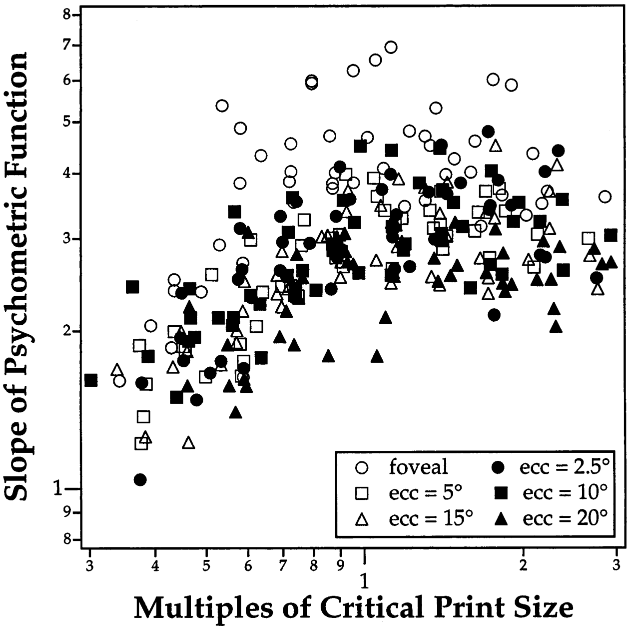

Fig. 6. The slope of psychometric function is plotted as a function of print size, expressed as multiples of the critical print size corresponding to the respective observer and eccentricity. Each datum represents the slope of one psychometric function for one observer and at one eccentricity. Data obtained from different eccentricities are represented by different symbols.

One potential explanation for the flatter slopes we obtained at smaller print sizes is that the reading performance with small print sizes may not reach 100%-correct. In our psychometric function analyses, we constrained the upper asymptote of the cumulative Gaussian to 100% correct. If the observers' performance had a lower asymptote, we may have artifactually forced the fitted curve to take on a flatter slope. However, close inspection of the raw data for all psychometric functions does not reveal a tendency for the psychometric functions to asymptote at a level lower than 100%. Thus we believe that the shallower slopes obtained for small print sizes is not an artifact of our curve-fitting procedure.

To examine the effect of the choice of criterion-level on our findings, we reanalyzed our data using criteria of 20, 35, 50, 65 and 95%-correct. Regardless of the criterion used, the major findings remain the same, i.e. critical print size increases as a function of retinal eccentricity, the shape of the reading speed versus print size plots are invariant and maximum reading speed decreases with eccentricity. Fig. 7 presents the results analyzed using the 50%-correct criterion, with reading speed plotted as a function of print size, and with eccentricity as a parameter. For each criterion used, we also determined the E_2 for critical print size and the RSVP exposure duration at maximum reading speed. Table 1 summarizes these E_2 factors for all six criteria. Across the six criteria, the E_2 for critical print size stays virtually constant, at about 1.4 deg. In contrast, the E_2 for exposure duration at maximum reading speed increases as the percent-correct criterion is lowered. In other words, if we allow more errors in calculating reading speed, the change in reading speed becomes less dependent on retinal eccentricity, whereas the change in the critical print size will be virtually unaffected by eccentricity. Note that for some extremely low percent-correct criteria, the dependency of reading speed on retinal eccentricity may in fact, vanish. Because reading for comprehension involves word recognition at higher accuracy, as opposed to scanning or skimming [39], we believe that our results obtained with higher percent-correct criteria are more pertinent to the task of reading.

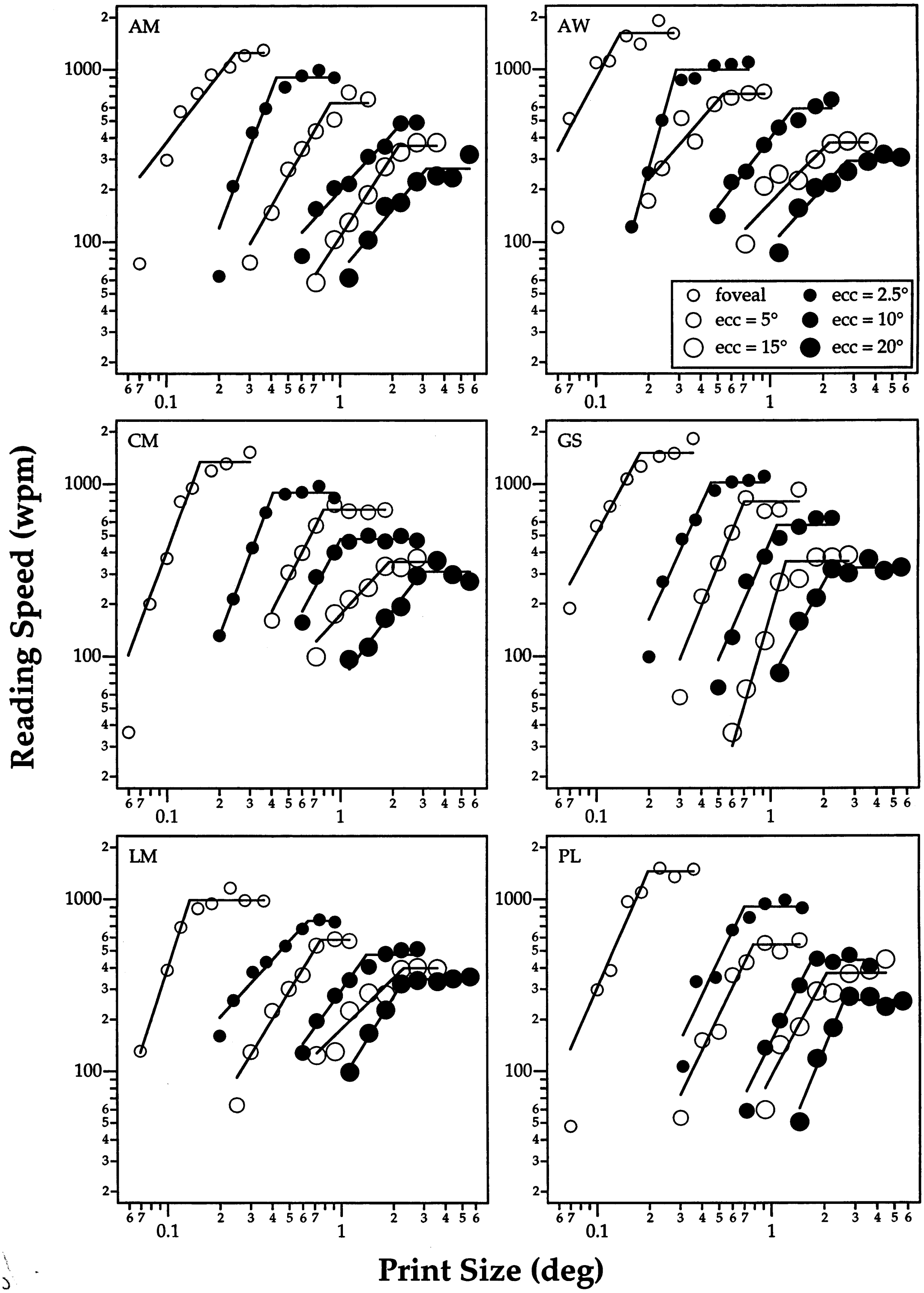

Fig. 7. Similar plots of reading speed versus print size as those given in Fig. 3 are presented for the same six observers, with a criterion of 50%-correct reading, instead of 80% as reported in the rest of the paper. Details of the figure are similar to those in Fig. 3.

4. Discussion

4.1. The scaling hypothesis

By determining reading speeds as a function of print size at six retinal eccentricities, we showed that (1) larger print size is required to achieve maximum reading speed in peripheral than in central vision; (2) the rate of change in reading speed as a function of print size remains invariant in central and peripheral vision and (3) even when print size is not the limiting factor, maximum reading speeds are still lower in peripheral than in central vision.

Our finding that larger critical print sizes are required in peripheral vision is not only consistent with the prediction from the scaling hypothesis, but also consistent with our understanding of spatial vision. Visual performance for spatial tasks such as contrast sensitivity, grating acuity and letter acuity are worse in peripheral than in central vision. However, by making the stimulus larger in size in peripheral vision, visual performance can be equated for tasks such as contrast sensitivity [20,21], Landolt C acuity [40,41], letter acuity [37], grating acuity [40,42] and Vernier acuity [36]. Note that a range of E_2 values have been reported for these and other spatial tasks, an effect attributed to the different substrates mediating these tasks in the visual system. Our goal in this study is not to speculate on the substrate in the visual system that underlies reading, but rather, we make use of E_2 as a tool to show the rate of change of reading performance in peripheral vision. Indeed, we found that asymptotic reading speed can always be achieved in peripheral vision, provided that sufficiently large letters are used.

We also found that the shapes of the reading speed versus print size plots are the same in central and peripheral vision. Theoretically, the shape invariance of these plots in the periphery suggests that only two variables are required to characterize the effects of print size on reading—the critical print size and the maximum reading speed. In other words, these speed versus print size plots can all be fitted with a single template, the horizontal and vertical positions of which can be calculated once we know the E_2 factors for the critical print size and the maximum reading speed.

Clinically, the rate of change in reading speed with print size can be viewed as the response to magnification. The shape invariance of the plots in central and peripheral vision suggests that the response to magnification is also invariant, at least within the central 20 deg of the visual field. However, we should keep in mind that our data pertain to peripheral viewing by normal subjects, and it remains possible that patients with central scotomata may show a different response to magnification.

Although the growth in critical print size and the shape-invariance of the data plots in peripheral vision are consistent with the scaling hypothesis, the hypothesis fails. Specifically, it does not account for the decline of maximum reading speeds in the periphery. In other words, print size is not the limiting factor for maximum reading speed in peripheral vision.

Table 1
E_2 factors (± 1 S.E.M.) for various criteria of reading accuracy

Criterion	E_2 for critical print size (deg)	E_2 for RSVP exposure duration at maximum reading speed (deg)
20%	1.38 ± 0.78	10.22 ± 1.63
35%	1.50 ± 0.80	7.90 ± 0.95
50%	1.28 ± 0.66	6.17 ± 0.70
65%	1.29 ± 0.83	5.22 ± 0.72
80%	1.39 ± 0.75	4.13 ± 0.78
95%	1.36 ± 0.83	2.77 ± 0.96

4.2. What factors limit reading speed?

Given the finding that print size is not the factor that limits maximum reading speed in normal peripheral vision, what then, are the limiting factors? One possible explanation for the decline in the maximum reading speed in peripheral vision is the reduction in the number of characters that can be recognized in a glance (the 'visual span'). Legge et al. [18] have presented data consistent with the idea that slow reading in normal central vision at low contrast, and reading speed deficits in some forms of low vision are attributable to a shrinkage in the visual span. More recently, Legge et al. [43] obtained evidence that the visual span indeed, reduces in size in the periphery. The inferred visual span reduced in size from at least 10 characters in central vision to about 2.8 characters at 15 deg eccentricity. This reduction in the size of the visual span approximately parallels the factor of 4.4 decrease in reading speed from fovea to 15 deg eccentricity. In a theoretical analysis, Legge et al. [44] have shown that reading speed is expected to vary nearly linearly with the size of the visual span.

If visual span is indeed a factor in limiting reading speed in peripheral vision, then a natural consequence arising from the reduction in visual span is that even with the RSVP reading paradigm, observers have to make intra-word saccades in order to read words that are longer than the width of their visual span. Rubin and Turano [16] showed that subjects with central field loss made intra-word saccades even when reading with the RSVP paradigm. In addition, they also provided evidence to show that reading speed changes inversely with the number of intra-word saccades, indicating that eye movements still play a role in limiting RSVP reading speed in peripheral vision.

Another plausible cause for slow reading in the periphery is the enhanced 'crowding' effect, also termed lateral masking. The crowding effect refers to the increased difficulty in recognizing a single letter flanked by other letters. Because the crowding effect is greater in peripheral vision [45,46], letter recognition in the periphery could be slower or less accurate than in the fovea, leading to slower reading. In fact, explanations based on crowding and reduced visual span may be linked because the reduction in the visual span may itself be a consequence of enhanced crowding. Recently, Latham and Whitaker [27] found that as long as large enough letter size is used, word recognition rate in peripheral vision can approach that in central vision. In their study, all ten words they used were three-letters long, which should all fall well within the visual span even at their maximum eccentricity of 10 deg [43]. We speculate that if they had used longer words, slower word recognition rates in peripheral vision might have been found.

The fourth possible explanation for the reduced maximum reading speed is slower temporal processing in the periphery. The RSVP paradigm requires the observer to process words presented in rapid succession. If the temporal processing is intrinsically slower in peripheral than central vision, then even if the visual span remains the same throughout the visual field, the number of words that can be processed within the same period of time will be fewer in peripheral vision. Indeed, several studies have documented a slower rate of processing of letters or words in the periphery [47–49].

4.3. Sentences versus random words

As discussed in Section 1, there are inconsistent findings regarding the advantage of context for reading in peripheral vision. Our results in Fig. 5 (square and diamond symbols) demonstrate a clear advantage of reading meaningful sentences over random-word sequences in the fovea, but that this advantage diminishes as the retinal eccentricity increases. There is an idiosyncrasy shown by individual observers: observer PL shows a bigger difference between reading meaningful sentences and random words at all eccentricities than observer AW. The idiosyncrasy is also shown, to some extent, by the two observers in the study of Latham and Whitaker [27] whose data are plotted in Fig. 5 for comparison (upward and downward triangles). These data were obtained by fitting their original sets of data with our two-line fit. In that study, observer KL demonstrates an advantage of reading sentences over random words at both the fovea and 5 deg eccentricity, and the magnitudes of the effect are very close to those we found. Observer FF, however, only shows a context advantage at the fovea but not at 5 deg eccentricity. Therefore, one potential explanation for the discrepancy between our results and those of Latham and Whitaker is individual differences. Another factor is the difference in the lexicon size used in the two studies: we had a total of 2219 words in our pool of sentences whereas Latham and Whitaker used only 400 words. The smaller lexicon used by Latham and Whitaker [27] might have made it easier for their observers to guess the random words even at 5 deg eccentricity. Note that both our study and that of Latham and Whitaker measured the effect of context in normal peripheral vision, it remains possible that the larger context effects observed by Bullimore and Bailey [12] and Fine and Peli [28] relate to differences in peripheral-field processing in patients with central scotomata.

4.4. E_2 factors

Using different criteria to define reading speeds, we obtained E_2 factors for critical print size close to 1.4 deg (Table 1). These values are very close to that reported for single-letter acuity ($E_2 \sim 1.5$ deg: [37]). The similarity of the E_2 factors for critical print size in reading and single-letter acuity has two implications: (1) the size ratio between critical print size and letter acuity remains constant across the visual field; and (2) the same neural factors that limit acuity in peripheral vision probably limit critical print size.

Because we only have foveal acuities for our observers, we could only calculate the size ratio between critical print size and letter acuity at the fovea. The average size ratio for the six observers and for a reading accuracy of 80%-correct, is 2.5 ± 0.3. This size ratio ranges between 2.2 and 2.7 when other accuracy-criteria of defining reading speed are used. If the size ratio between the critical print size and letter acuity is constant across the visual field, we can estimate the print size that is required for a person to read at his/her maximum reading speed at any retinal eccentricity, as long as we know the letter acuity at the fovea. Note that the above implication regarding a constant size ratio between critical print size and letter acuity is drawn based upon similar E_2 values obtained from *different* groups of observers. Whether or not the size ratio between critical print size and local letter acuity is indeed constant for various retinal eccentricities in the same group of observers remains to be determined.

We found that E_2 values for exposure duration at maximum reading speed increased from 2.8 to 10.2 deg as the accuracy-criterion decreased from 95 down to 20%-correct. One possible explanation for this change in E_2 is that our calculation of reading speed did not correct for reading errors. Reanalyses of the data, using reading speeds that were corrected for reading errors (see Section 2.2 for details), yielded E_2 values that are very similar to those we originally had. Consequently, we conclude that our method of calculating reading speeds does not explain the change in E_2 values obtained for different accuracy-criteria.

4.5. Clinical implications

In addition to confirming the clinical wisdom that reading in peripheral vision is slow and requires large print, our empirical findings have three clinical implications for rehabilitation of low-vision patients with central visual field defects. First, reading using the peripheral visual field is always possible and of functional value, as long as large enough print size is used. Second, even with large enough print, reading speed is always slower in peripheral than central vision. Therefore, we can expect low vision patients having central visual field defects to read more slowly than they did before the onset of the central field defect. Third, the change in reading speed as a function of print size, or, the response to magnification, remains invariant in central and peripheral vision, at least for healthy retina. Thus, despite the lower maximum reading speed attainable in peripheral vision, low vision patients who have central visual field defects would still benefit from magnification in a similar way as those with intact central fields. Practically, this means that we should still provide patients with central visual field defects the magnification that is necessary to bring the print to the critical print size. Because we have determined that the size ratio between the critical print size and single-letter acuity is about 2.5, therefore, a good rule-of-thumb for estimating the initial magnification is to magnify print to a size that is at least 2.5 times as large as the patient's local letter acuity. Of course, the final magnification that is going to be prescribed will depend on a lot of other factors, such as the type of magnifying devices and whether or not the patient uses the same retinal locus for reading single letters and words.

There are some limitations on these clinical recommendations. First, reading with the RSVP paradigm is a different task from the conventional page-reading task. To apply our conclusions to everyday reading, other factors that are pertinent to the conventional reading task should be taken into consideration. These factors include oculo-motor limitations and manipulation of a magnifier. Second, patients with central visual field defects might have unhealthy and compromised peripheral retina. Our findings, based on observers with healthy peripheral retina might not be directly applicable to these patients. It is also possible that patients who have central field defects may perform better in the periphery than normal subjects, because of their long-term adaptation to the presence of a central scotoma. Third, most patients who develop central scotomata are elderly, and there may be an effect of age on the results. Several studies have documented an interaction between age and the use of peripheral vision [50,51]—older subjects demonstrated more difficulty in extracting visual information from the periphery than younger subjects. Fourth, the slope of the psychometric functions relating the accuracy of reading to the word-presentation rate are flatter in low vision subjects with central visual field defects tested using a similar experimental paradigm [52]. Despite these limitations, our findings have quantified reading performance in normal peripheral vision, and these measurements provide a framework for understanding the reading performance of low-vision patients with central scotomata.

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Appendix. Titles of books used in the study.

Main Street by Sinclair Lewis
Mansfield Park by Jane Austen
Persuasion by Jane Austen
Sense and Sensibility by Jane Austen
The Crossing by Winston Churchill
The Little Princess by Frances Hodgson Burnett
The Market Place by Harold Frederic
The Shuttle by Frances Hodgson Burnett
The Turn of the Screw by Henry James

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