

Amblyopic reading is crowded

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We measure acuity, crowding, and reading in amblyopic observers to answer four questions. (1) Is reading with the amblyopic eye impaired because of larger required letter size (i.e., worse acuity) or larger required spacing (i.e., worse crowding)? The size or spacing required to read at top speed is called “critical”. For each eye of seven amblyopic observers and the preferred eyes of two normal observers, we measure reading rate as a function of the center-to-center spacing of the letters in central and peripheral vision. From these results, we estimate the critical spacing for reading. We also measured traditional acuity for an isolated letter and the critical spacing for identifying a letter among other letters, which is the classic measure of crowding. For both normals and amblyopes, in both central and peripheral vision, we find that the critical spacing for reading equals the critical spacing for crowding. The identical critical spacings, and very different critical sizes, show that crowding, not acuity, limits reading. (2) Does amblyopia affect peripheral reading? No. We find that amblyopes read normally with their amblyopic eye except that abnormal crowding in the fovea prevents them from reading fine print. (3) Is the normal periphery a good model for the amblyopic fovea? No. Reading centrally, the amblyopic eye has an abnormally large critical spacing but reads all larger spacings at normal rates. This is unlike the normal periphery, in which both critical spacing and maximum reading rate are severely impaired relative to the normal fovea. (4) Can the uncrowded-span theory of reading rate explain amblyopic reading? Yes. The case of amblyopia shows that crowding limits reading solely by determining the uncrowded span: the number of characters that are not crowded. Characters are uncrowded if and only if their spacing is more than critical. The text spacing may be uniform, but the observer’s critical spacing increases with distance from fixation, so the uncrowded span extends out to where the spacing is critical. Amblyopes have normal critical spacing in the periphery, so, when the uncrowded span extends into the periphery, it has normal extent, which predicts our finding that reading rate is normal too. This confirms the theory that reading rate is determined by the width of the uncrowded span, independent of the critical spacing within the span. The uncrowded-span model of normal reading fits the amblyopic results well, with a roughly fivefold increase in the critical spacing at fixation. Thus, the entire amblyopic reading deficit is accounted for by crowding.

Keywords: amblyopia, crowding, critical spacing, reading, RSVP, peripheral vision, critical print size (CPS), uncrowded span

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Introduction

Amblyopia is a developmental visual disorder typically affecting just one eye and usually associated with childhood strabismus, anisometropia, or form deprivation. Amblyopes have extensive crowding and reduced visual acuity, contrast sensitivity, and position acuity (Ciuffreda, Levi, & Selenow, 1991; McKee, Levi, & Movshon, 2003). We observe that amblyopes cannot read fine print with their amblyopic eye. This article asks whether the effects of amblyopia on reading are mediated by worsened acuity or crowding. Specifically, we wondered whether the “uncrowded span”, which limits normal reading, also limits amblyopic reading.

Crowding in peripheral and amblyopic vision

In peripheral vision, a letter that is easily recognized on its own becomes unrecognizable if surrounded by other letters. This “crowding” phenomenon (Stuart & Burian, 1962) has been discussed scientifically for some 60 years but is only beginning to be understood (for review, see Pelli, Palomares, & Majaj, 2004; Strasburger, 2003). Crowding in the amblyopic fovea was first reported by Irvine (1945), “single letters or the direction of ... an E could be identified by the amblyopic eye, if viewed one letter at a time, but when placed in conjunction with other letters in a line, confusion affected the interpretation”. At about the same time, the ophthalmologist Hermann Burian noted that his orthoptist recorded better visual acuities in

amblyopic patients than he did. The orthoptist used isolated letters to measure acuity, whereas he used letters arranged in a row (Burian & von Noorden, 1974). The phenomenon of crowding in amblyopia has been repeatedly confirmed (Bonneh, Sagi, & Polat, 2004; Flom, Weymouth, & Kahneman, 1963; Hariharan, Levi, & Klein, 2005; Hess, Dakin, Tewfik, & Brown, 2001; Hess & Jacobs, 1979; Levi & Klein, 1985; Levi, Hariharan, & Klein, 2002a; Stuart & Burian, 1962). Interest in crowding is growing quickly, with many recent publications, including this special issue of the *Journal of Vision*.

Amblyopic and peripheral vision are similar in many ways, including crowding (e.g., Levi, 1991; Levi & Klein, 1985; Levi, Klein & Aitsebaomo, 1985; Levi, Klein, & Wang, 1994a, 1994b), and both are unlike blurred foveal vision. As Irvine (1945) noted, “If the good eye is blurred to a visual acuity equal to that of the amblyopic eye the contrast to the patient is obvious, i.e., to the good eye the minimal visible letter is blurred and hazy, whereas to the amblyopic eye it is black, easily seen, but is uninterpretable”. This is also true in normal peripheral vision (see flanked letter in Figure 1).

Crowding is characterized by the “critical” center-to-center spacing of target and flankers required to achieve a threshold level of performance identifying the target. The critical spacing is proportional to eccentricity and extends only 0.1° in the normal fovea (Bouma, 1970; Liu & Arditi, 2000; Toet & Levi, 1992). A few papers have applied the label “foveal crowding” to longer range effects in the normal fovea, but, unlike real crowding, these effects are dependent on target size and

can be explained by contrast masking (Levi, Klein, & Hariharan, 2002). Real crowding, in peripheral vision and in the central field of strabismic amblyopes, is largely independent of target (and flanker) size and cannot be explained by contrast masking (Hariharan et al., 2005; Levi et al., 2002, 2002a, 2002b; Pelli et al., 2004; Strasburger, Harvey, & Rentschler, 1991; Tripathy & Cavanagh, 2002).

We live in cluttered visual environments, so crowding makes most of the objects in most of our visual field unrecognizable. Understanding crowding may help us model object recognition in normal and abnormal vision (Neri & Levi, 2006; Pelli et al., 2004; Wilson, 1991).

Reading in peripheral and amblyopic vision

Reading is key to modern life. Anecdotes and the few extant studies report that reading through the amblyopic eye is impaired (e.g., Bach, Strahl, Waltenspiel, & Kommerell, 1990; Stifter et al., 2005a, 2005b). “Cases of high visual acuity for crowded Landolt Cs were always associated with fast reading; cases of low visual acuity for crowded Landolt Cs were associated either with slow or fast reading” (Bach et al., 1990). In normal vision, reading more peripherally is increasingly slower, even if the letter size and spacing are scaled with eccentricity (e.g., Chung, 2002; Chung, Mansfield, & Legge, 1998; but see Latham & Whitaker, 1996). Understanding the factors that limit reading in peripheral vision or amblyopia would advance visual science and might lead to help for people with central field loss (Legge, Rubin, Pelli, & Schleske, 1985) or amblyopia. Amblyopes read at normal rates with their better eye but run a disproportionate risk of losing that eye (Vereecken & Brabant, 1984).

Acuity, crowding, and reading

Here, we test whether the effects of amblyopia on acuity and crowding account for the amblyopic effect on reading. Our approach is to measure acuity, crowding, and reading and compare them. We measure performance for three tasks: isolated letter identification, flanked letter identification, and reading (Figure 1). While maintaining the eccentricity of the target, we shrink the whole stimulus, so size and spacing covary. The first task uses an isolated letter, so spacing is infinite and only size can matter (Figure 1, left). The second task uses flanking letters to induce crowding. Can the size and spacing requirements for these two tasks, identification of a letter, isolated or flanked, with unlimited response time, predict the demands of the third task, reading?

It is straightforward to measure and compare the critical spacing for reading with the critical spacing for crowding. This is assumption-free. If the reading of words is limited by the crowding of the letters, then we predict that both tasks will have the same critical spacing. However, the

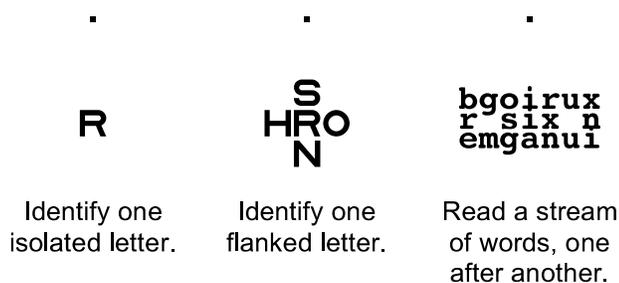


Figure 1. Three tasks. While fixating a mark, the observer is asked to identify one isolated letter (left) or one letter surrounded by random flanking letters (middle) or to read a stream of words (e.g., “garage six blocks away and when”), presented one after another (RSVP), each surrounded by new random flanking letters (right). In each case, we use an adaptive procedure to determine the critical size (covaried with spacing) for 50% correct identification. It is of no consequence, but the actual stimuli differed from this illustration in using different fixation marks and using bright (instead of dark) letters for the two letter-identification tasks (see [Methods](#)). Our measurement of flanked and unflanked acuity to test for crowding is computerized, but is otherwise similar to older printed tests, such as Tommila’s (1972) flanked and unflanked tumbling E charts and the Cambridge Crowding Cards (Atkinson, Anker, Evans, Hall, & Pimm-Smith, 1988).

values depend somewhat on the arbitrary criteria used for “critical” in two very different tasks. What fraction of maximum reading rate is “critical”? What proportion correct of letter identifications is “critical”? With only arbitrary answers to those questions, we can only predict proportionality of the two estimates of critical spacing, not equality. That is the best we can do without assumptions. We can do better by adding an assumption. Linking the two tasks, the uncrowded-span model of reading rate predicts the reading rate curve resulting from any given critical spacing for crowding and threshold criterion for letter identification (Pelli et al., 2007, this issue). The reader can have it both ways. We apply both the assumption-free test and, at the cost of an assumption, the more stringent test.

The uncrowded-span model joins Bouma’s (1970) observation that the critical spacing of crowding is determined by eccentricity with the Legge, Mansfield, and Chung (2001) conjecture that reading rate is proportional to the *visual span*: the number of characters that can be identified without moving one’s eyes. Pelli et al. (2007, this issue) show that the visual span is the *uncrowded span*: the number of character positions in a line of text that are uncrowded, that is, spaced apart more than the critical spacing. This number depends on the letter spacing and the vertical position in the visual field. Crowding is more extensive at greater eccentricity, so, for a given vertical eccentricity, the uncrowded region extends left and right to the horizontal eccentricities at which the observer’s critical spacing equals the letter spacing of the text. The uncrowded-span theory is that reading rate is proportional to the uncrowded span. This gives a good account for how reading rate depends on letter spacing in normal observers. Here, we apply it to reading by amblyopes. Pelli et al. show that crowding limits reading in normal vision. Does crowding also limit reading in amblyopic vision?

No escape

Since crowding depends solely on the ratio of actual to critical spacing, it is tempting to think that if we enlarge the text enough, it will all escape from crowding. We flailed for a year in the grip of this misconception, which assumes that crowding is uniform within a word. Letters in text may be uniformly spaced, but the observer’s critical spacing increases with distance from fixation. Crowding is not uniform within a word.

Instead of focusing on the degree of crowding at a point, to understand reading, it is better to take a step back and note the width of the region within which letters are uncrowded. Reading is confined to that uncrowded region. Its span determines reading rate (Pelli et al., 2007). There is no escape.

The uncrowded-span model, in brief

The uncrowded-span model consists of three assumptions, which we present here, and some intricate calculations, for

which we refer the interested reader to the Pelli et al. Appendices A, B, and C. (This section is optional.)

The idea is that observers read only the uncrowded letters. In some central field, letters are spaced more than the critical spacing and are not crowded. Beyond that field, in the periphery, letters are spaced less than the critical spacing and are crowded. Thus, the central field is uncrowded and the remaining peripheral field is crowded. The uncrowded span u is the number of uncrowded letter positions for the given text’s letter spacing and vertical eccentricity.

The uncrowded-span theory is that reading rate r is proportional to the uncrowded span,

$$r = \rho u, \quad (1)$$

where ρ is a proportionality constant with a value on the order of 100 words/min. This is Legge’s “visual span” conjecture, updated to reflect the proof that the visual span is actually the uncrowded span. Equation 1 is the key assumption of the uncrowded-span model. Two ancillary assumptions, Bouma’s law and dither, enhance the model to predict realistic reading rate curves without extensive measurements of critical spacing.

Bouma’s law says that critical spacing s of horizontal text grows with eccentricity ϕ and is $s = s_0 + b\phi$ on the horizontal midline and $s = s_0 + b\phi/\varepsilon$ at the vertical midline, where s_0 is the critical spacing at zero eccentricity, $\varepsilon = 2$ is the ellipticity, and b was once thought to be a constant but is now known to depend on eccentricity $b = b_1 + b_2\phi$ (Pelli et al., 2007). Given Bouma’s law, a geometric analysis shows that the uncrowded span is

$$u = 1 + \frac{2s - s_0}{b} \frac{1}{s} \times \sqrt{\frac{1}{2} + \frac{1}{2} \sqrt{1 + 4(\varepsilon^2 - 1) \frac{b^2 \phi_v^2}{(s - s_0)^2} - \frac{b^2 \phi_v^2}{(s - s_0)^2}}}, \quad (2)$$

where s is spacing and ϕ_v is the vertical eccentricity.

Plotting reading rate r versus spacing s produces a curve consisting of a nearly vertical cliff at the critical spacing

$$s = s_0 + \frac{b\phi_v}{\varepsilon} \quad (3)$$

and an asymptotically horizontal plateau,

$$r \approx \rho \left(1 + \frac{2}{b} \right). \quad (4)$$

The maximum reading rate r_{\max} may be slightly higher than the asymptote.

$$\begin{aligned} r_{\max} &= \rho \left(1 + \frac{2}{b} \right) && \text{if } \varphi_v = 0 \\ r_{\max} &\approx \rho \left(1 + \frac{2}{b} 1.15 \right) && \text{if } \varphi_v \gg \frac{s_0}{b} \text{ and } \varepsilon = 2 \end{aligned} \quad (5)$$

This simple model assumes an abrupt step in performance, from chance (crowded) to perfect (uncrowded), as the spacing is increased beyond the critical value, whereas the human letter-identification and reading-rate functions are known to increase gradually. The full model produces human-like reading-rate functions by adding *dither*: random trial-to-trial variation of the critical spacing, with a uniform probability distribution over a 0.55 log-unit range of spacing. The model's predicted reading rate is the average of the instantaneous rate r over the distribution of possible values of the critical spacing (Equation C1 in Pelli et al.). This smears out the step-like reading rate function of Equations 1 and 2 along the log spacing axis to yield a ramp-like function that fits the human data well. The model's estimated critical spacing is the P th quantile of the dithering range, where P is the (arbitrary) critical probability of letter identification, corrected for guessing. Table 2 summarizes each fit (Equations C1 and B10 in Pelli et al., 2007) by its critical spacing (Equation 3) and maximum reading rate.

Our results bear on the uncrowded-span model in three ways. First, the normal model fits the amblyopic results well, with a roughly fivefold increase in critical spacing at fixation and no change in the larger critical spacings found more peripherally. Second, we find that identifying a flanked letter and reading a stream of words have the same critical spacing. This is strong evidence that crowding limits both. Third, the case of amblyopia tests a key assumption of the model, showing that reading rate is determined by the span of the uncrowded region, independent of the critical spacing within.

Size or spacing?

This article breaks with a long tradition of plotting reading rate as a function of letter size. Knowing that one must recognize the letters in order to read the word, Plato and many since have supposed that letter acuity determines the print size needed for reading: “Lacking keen eyesight, we were told to read small letters from a distance” (Plato). The classic reading rate curve perpetuates the assumption that size matters even when observers are well corrected. The classic experiment measures and plots reading rate as a function of print size, but one could equally well plot it as a function of letter spacing, since both vary together. However, as shown in the companion paper and here, for well-corrected

observers, the size is irrelevant. Only the spacing matters. Thus, when there is a choice, our reading graphs display the (relevant) spacing instead of the (irrelevant) size.

Methods

Our methods are nearly identical to those of Pelli et al. (2007). As illustrated in Figure 1, we measure visual acuity for isolated or flanked letters and compare the two acuities with the critical spacing for reading.

Computer and display

All experiments were performed with an Apple G4 PowerBook computer using MATLAB software with the Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997). Stimuli were presented on a gamma-corrected Sony G400 monitor with the (green) background luminance set to 30 cd/m², which is at the middle of the monitor's range (Pelli & Zhang, 1991).

Isolated and flanked letter acuities

For each eye and eccentricity, we make two parametric measurements of letter identification. One of these (flanked acuity) covaries size and spacing of the letters. By itself, this measurement would confound size and spacing. However, we also make a comparable measurement of isolated letter acuity, that is, with infinite spacing. Measuring the size threshold with two different spacings (1.1 times the size and infinite) allows us to disentangle the two, showing that flanked acuity is much larger than and, thus, not limited by unflanked acuity.

The fixation mark consisted of four black diagonal lines (0.1° thick) forming an X (2° wide and 2° high) with the center spared (a 1° gap). Observers were instructed to fixate the invisible intersection point of the lines. The fixation mark was displayed for the entire trial. The signal, either alone (isolated letter acuity) or flanked by four letters (flanked acuity), appeared at the center of the screen for 200 ms. Signal eccentricity was controlled by varying the position of the fixation mark on the screen. The signal was presented either centrally (centered at fixation) or at 5° or 10° in the lower visual field. The signal (and each flanker, if present) was always 1 of the 10 letters of the Sloan alphabet (CDHKNORSVZ), randomly selected, displayed at 90% contrast as a bright green letter on a dimmer green background. (The Sloan font is available from <http://psych.nyu.edu/pelli/software.html>.) Letter contrast is defined as the ratio of luminance increment to background. Each signal presentation was accompanied by a beep. A response screen followed, showing all

the possible signals. Observers identified the signal by using a mouse-controlled cursor to point and click on their answer. Correct identification was rewarded with a beep.

The Sloan font is uppercase only. All letters have the same height and width, and we take the letter “size” to be the letter height, which equals the letter width. For flanked letters, the center-to-center spacing was 1.1 times the letter size, horizontally and vertically (Figure 1). We adjusted the size of the quintuplet (i.e., target and four flankers) by QUEST (Watson & Pelli, 1983), to measure critical spacing for 50% correct. “Critical” is a synonym for “threshold”. Our threshold criterion is 50% correct. Each run of 40 trials yields one threshold estimate. Thresholds presented here are the geometric mean of at least four replications of each condition.

(In our results, Table 2, the standard deviation of the log flanked acuity across observers is higher than that for unflanked acuity and that for critical spacing of reading. Future investigators might try to reduce this standard deviation by increasing the number of trials per run or the number of runs, to better expose the individual differences.)

Our measurements of flanked letter acuity covary size and spacing to determine the critical value. This has several practical advantages. It saves time by reducing the two-dimensional space of size versus spacing to just one dimension, spacing = 1.1 times the size. Moreover, it allows us to use the same procedure for isolated and flanked letters. It enables measurement of small critical spacings without overlapping the letters. It allows testing with normal text spacing over the whole range, reinforcing its relevance to reading.

The cost of covariation is that it confounds the variables. However, for well-corrected observers identifying normally spaced letters, past studies and new experiments presented here find that peripheral and amblyopic letter identification is limited by the center-to-center spacing, *not* the letter size (Hariharan et al., 2005; Levi et al., 2002a, 2002b; Pelli et al., 2004, 2007; Strasburger et al., 1991; Tripathy & Cavanagh, 2002). As noted above, measuring the size threshold with two different spacings enables us to distinguish the effects of letter size and spacing.

When comparing critical spacing across studies, one should bear in mind that its value depends on the threshold criterion (see Pelli et al., 2007; Figure 8).

Reading

Our observers read aloud six words per trial, presented on a computer monitor, one word at a time. Rapid serial visual presentation (RSVP) minimized the need for eye movements (Potter, 1984). Each word was presented centrally, at fixation, or at 5° or 10° in the lower visual field. The text was taken from the Mary Higgins Clark (1991) murder mystery *Loves Music, Loves to Dance* and was shown in the original word order. No observer saw

the same text twice. The average word length was five characters. The text was presented in the Courier font (Bitstream “Courier 10 Pitch Bold”) as black letters on the green screen.

We note that crowding and reading were tested with different letter polarities, light and dark; however, this is inconsequential since reading speed is independent of contrast polarity (Legge, Pelli, Rubin, & Schleske, 1985). Similarly, using letters at threshold contrast (for identification in isolation), Ramakrishna Chakravarthi (personal communication) found no difference in the crowding of white letters by white flankers versus the crowding of black letters by black flankers.

For the mixed-case text used for reading, we define letter “size” as x-height. Letter “spacing” is always center to center. This font (Courier) has one uniform spacing and the size was 0.9 times the spacing. For central reading, the fixation mark was two black squares centered above and below the center of the word. For peripheral reading, the fixation mark was a single black square. To mimic ordinary reading of a printed page, random letters were presented above and below and on either side of the word with the same spacing horizontally and vertically (Figure 1). New random flanking letters were presented with each word. We also presented a random letter string, in place of the word, at the beginning and end of each trial, before the first word and after the last word.

We used QUEST to estimate reading rates to achieve 50% correct for each condition. We tested seven or eight print sizes. In each trial, observers were shown six words. Observers read the six words out loud with unlimited speaking time. Reading rate is defined as the rate at which words are presented when the observer achieves the 50% threshold criterion. At the end of each trial, an answer screen displayed the six words, and the experimenter counted the words read incorrectly. Credit was given for correctly read words regardless of word order. Each run consisted of 20 trials. QUEST increased or decreased presentation rate following each trial to determine threshold RSVP reading rate at 50% accuracy. Thresholds presented here represent the geometric mean of at least three replications of each condition.

Observers

We tested seven amblyopes (two anisometric, two strabismic, and three who are both anisometric and strabismic—see Table 1) and two normal observers who did not know the purpose of these experiments. The symbol color in our figures indicates amblyopic etiology: red for strabismic, green for anisometric, and blue for those who are both anisometric and strabismic. All observers were tested monocularly: normals with their preferred eye and amblyopes with each eye separately. Observers had or were given substantial experience (hundreds or thousands of

Observer	Age (years)	Gender	Strabismus (at 6 m)	Eye	Refractive error (diopter)	Line letter acuity (isolated letter acuity) ^a
Strabismic						
A.P.	19	F	L EsoT 4 ^Δ and L hyper 2 ^Δ	R	−1.50/−0.50 × 180	20/12.5 ^{−2}
				L	−0.75/−0.25 × 5	20/50 (20/32 ⁺¹)
J.S.	22	F	L EsoT 6–8 ^Δ and hyperT 4–6 ^Δ	R	+1.25	20/16
				L	+1.00	20/40 (20/32 ⁺¹)
Anisometropic						
S.C.	27	M	None	R	+0.50	20/16 ⁺²
				L	+3.25/−0.75 × 60	20/50 ⁺² (20/40 ^{−2})
C.J.	22	M	None	R	−15.00/−1.25 × 150	20/125 ^{−4} (20/125 ⁺¹)
				L	−6.00	20/16 ^{−2}
Strabismic and anisometropic						
S.M.	55	F	Alt. ExoT 18 ^Δ	R	+2.75/−1.25 × 135	20/40 (20/25 ⁺¹)
				L	−2.00	20/16 ^{−2}
J.D.	19	M	L EsoT 3 ^Δ	R	+2.50	20/16
				L	+5.00	20/125 (20/125 ⁺²)
A.W.	22	F	R EsoT 4–6 ^Δ and hypoT 4 ^Δ	R	+2.75/−1.0 × 160	20/80 ^{−1} (20/50 ^{−1})
				L	−1.00/−0.50 × 180	20/16 ^{−1}

Table 1. Observer characteristics. Note: ^aThe acuities listed in this table were determined using a Bailey–Lovie chart. We specify both the full-line letter acuity and the isolated letter acuity.

trials) in experiments, like this one, that required peripheral viewing. The experimenter monitored the observers' eye position to ensure that fixation was maintained, discarding the few trials in which it was not.

The two-line fit

We fit our reading-versus-spacing data in two ways. The two-line fit described by Chung et al. (1998) provides estimates of critical print size (CPS) and maximum reading rate. Applied to a graph of log reading rate versus log size (or spacing), the two-line fit consists of two lines that join at a “critical” point. The left-side line (the cliff) has arbitrary positive slope, optimized to fit the data. The right-side line (the plateau) has zero slope. This fit has three degrees of freedom: the (x, y) coordinates of the point (critical size or spacing and maximum reading rate) and the slope of the cliff.

Fitting the uncrowded-span model

Fitting the uncrowded-span model (Pelli et al., 2007, their Equations C1 and B10) similarly provides maximum reading rate and critical spacing for reading. The results of both fits and the isolated and flanked letter acuities of all observers appear in Table 2. Comparing the two-line and uncrowded-span fits shows that the CPS for reading provided by the two-line fit is proportional to $(1.5\times)$ the critical spacing for reading provided by the

uncrowded-span fit (Table 2, eighth column). Our graphs show the uncrowded-span fits.

The uncrowded-span model assumes that $r = \rho u$, where r is reading rate, ρ is a proportionality constant with a value on the order of 100 words/min, and u is the uncrowded span (Equation 1). Specifically, we fit Equations C1 and B10 in Pelli et al. (2007) to the reading rate versus spacing data (our Figures 3 and 4) to estimate the three model parameters, s_0 , b , and ρ . We set the threshold criterion P to 0.44 to match our letter-identification task criterion of 50%, after correction for guessing (0.1 for the 10-letter Sloan alphabet). We optimized s_0 and fixed $b = 0.5$ in our fits to reading rates at 0° eccentricity. For each eye, the fits to the data collected at 5° and 10° eccentricity optimized b and fixed s_0 to the value estimated from the data collected at 0°. The fitted value of s_0 was about 0.1° in normals, roughly twice that in nonamblyopic eyes, and roughly five times normal (range = 0.52° to 1.5°) in the amblyopic eyes (Table 2). For each fit, Table 2 also provides the maximum reading rate and the critical spacing (Equation 3). The MATLAB program FitAmblyopes.m that fit the uncrowded-span model to our reading rate versus spacing data is available at <http://psych.nyu.edu/pelli/software.html>.

The RMS error of the two-line fit, which has three degrees of freedom, is slightly lower than that of the uncrowded-span model, which has only two degrees of freedom (Table 2) at any given eccentricity. Removing the third degree of freedom from the two-line fit by fixing the slope of the cliff, or adding a third degree of freedom to the uncrowded-span model, by optimizing the dithering range for each fit, would make the errors more comparable and more similar.

Eccentricity (deg)	Eye	Observer	Maximum reading rate			Critical spacing for reading		Critical print size (CPS)		RMS error in log reading rate		Critical spacing for crowding		Acuity		Uncrowded-span model parameters												
			Uncrowded-span		Two-line fit		Uncrowded-span model		Two-line fit (deg)		Ratio		Uncrowded-span model fit		Two-line fit		Flanked letter acuity × 1.1 (deg)		Isolated letter acuity (deg)		Ratio		b		ρ (words/min)		s ₀ (deg)	
			model fit (words/min)	Two-line fit (words/min)	Ratio	fit (deg)	Two-line fit (deg)	Ratio	model fit	Two-line fit	Ratio	model fit	Two-line fit	Flanked letter acuity × 1.1 (deg)	Isolated letter acuity (deg)	model fit	Two-line fit	Flanked letter acuity × 1.1 (deg)	Isolated letter acuity (deg)	model fit	Two-line fit	Flanked letter acuity × 1.1 (deg)	Isolated letter acuity (deg)	model fit	Two-line fit	Flanked letter acuity × 1.1 (deg)	Isolated letter acuity (deg)	model fit
0	Norm.	A.F.	738	581	0.79	0.08	0.21	2.63	0.06	0.03	0.12	0.08	0.50	126	0.08													
0	Norm.	E.J.	493	321	0.65	0.12	0.20	1.68	0.09	0.05	0.19	0.14	0.50	99	0.12													
0	NAE	A.P.	499	314	0.50	0.19	0.24	1.09	0.22	0.08	0.27	0.17	0.50	100	0.19													
0	NAE	A.W.	648	316	0.49	0.17	0.20	1.18	0.11	0.04	0.17	0.11	0.50	130	0.17													
0	NAE	C.J.	610	430	0.70	0.09	0.16	1.78	0.07	0.03	0.17	0.11	0.50	122	0.09													
0	NAE	J.D.	353	275	0.78	0.07	0.17	2.43	0.09	0.07	0.12	0.09	0.50	71	0.07													
0	NAE	J.S.	519	305	0.59	0.16	0.22	1.38	0.11	0.03	0.13	0.08	0.50	104	0.16													
0	NAE	S.C.	607	299	0.49	0.16	0.19	1.19	0.10	0.06	0.11	0.09	0.50	121	0.16													
0	NAE	S.M.	431	213	0.49	0.20	0.26	1.30	0.10	0.09	0.27	0.13	0.50	86	0.20													
0	AE	A.P.	300	230	0.58	0.53	0.92	1.48	0.16	0.09	0.64	0.22	0.50	60	0.53													
0	AE	A.W.	645	265	0.41	0.89	1.08	1.21	0.17	0.06	0.72	0.28	0.50	129	0.89													
0	AE	C.J.	961	316	0.33	1.19	1.18	0.99	0.13	0.08	0.93	0.51	0.50	192	1.19													
0	AE	J.D.	361	279	0.77	0.59	1.43	2.42	0.09	0.09	0.76	0.41	0.50	72	0.59													
0	AE	J.S.	512	263	0.51	0.43	0.41	0.95	0.19	0.07	0.26	0.10	0.50	102	0.43													
0	AE	S.C.	547	280	0.51	0.47	0.55	1.17	0.14	0.04	0.33	0.22	0.50	109	0.47													
0	AE	S.M.	313	165	0.53	0.43	0.54	1.26	0.09	0.08	0.45	0.20	0.50	63	0.43													
5	Norm.	A.F.	161	137	0.85	1.91	2.44	1.28	0.11	0.08	2.06	0.30	0.73	39	0.08													
5	Norm.	E.J.	168	143	0.85	1.53	2.21	1.44	0.06	0.03	1.32	0.34	0.56	33	0.12													
5	NAE	A.W.	226	199	0.88	1.41	2.08	1.48	0.07	0.06	1.66	0.38	0.50	40	0.17													
5	NAE	C.J.	—	—	—	—	—	—	—	—	2.02	0.94	—	—	—													
5	NAE	J.D.	—	—	—	—	—	—	—	—	0.49 ^a	—	—	—	—													
5	NAE	J.S.	127	113	0.89	1.39	1.93	1.39	0.07	0.05	1.15	0.31	0.49	22	0.16													
5	NAE	S.C.	201	188	0.94	1.81	3.53	1.95	0.07	0.08	1.01 ^a	0.52	0.66	45	0.16													
5	NAE	S.M.	126	113	0.90	1.31	1.91	1.46	0.12	0.09	2.34	0.39	0.45	20	0.20													
5	AE	A.W.	270	176	0.65	1.73	2.44	1.41	0.07	0.07	1.65	0.43	0.34	34	0.89													
5	AE	C.J.	—	—	—	—	—	—	—	—	2.30	—	—	—	—													
5	AE	J.D.	—	—	—	—	—	—	—	—	0.92 ^a	0.61	—	—	—													
5	AE	J.S.	151	115	0.76	1.53	2.07	1.35	0.11	0.05	1.32	0.26	0.44	24	0.43													
5	AE	S.C.	217	176	0.81	1.82	2.67	1.47	0.06	0.03	0.90 ^a	0.41	0.54	41	0.47													
5	AE	S.M.	115	94	0.82	1.46	2.26	1.55	0.09	0.07	1.83	0.77	0.41	17	0.43													
10	NAE	J.D.	161	168	1.04	2.39	3.99	1.67	0.15	0.07	2.07	0.57	0.46	27	0.07													
10	NAE	S.C.	49	37	0.76	2.44	3.17	1.30	0.05	0.11	2.99	0.65	0.46	8	0.16													
10	NAE	A.W.	—	—	—	—	—	—	—	—	3.40	0.64	—	—	—													
10	AE	J.D.	206	152	0.74	2.50	3.21	1.28	0.09	0.03	1.98	0.82	0.38	29	0.59													
10	AE	S.C.	33	27	4.61	2.40	3.42	1.43	0.09	0.08	2.81	0.43	0.39	5	0.47													
10	AE	A.W.	—	—	—	—	—	—	—	—	3.51	0.58	—	—	—													

Table 2. Parameters of the fits to the reading rate data (Figures 4 and 5). The uncrowded-span (Pelli et al., 2007, their Equations C1 and B10) and two-line (Chung et al., 1998) fits and the flanked and isolated letter acuity measurements are described in the Methods section. The critical spacing for reading $s_0 + b\phi_v/2$ (Equation 3) and the maximum reading rate are for the uncrowded-span model with parameters b , ρ , and s_0 . ρ is specified here in words per minute; one must divide it by 10 to convert it into Hertz. When fitting the uncrowded-span model at zero vertical eccentricity $\phi_v = 0$, the critical spacing depends on s_0 and is independent of b , so we fix b at an arbitrary value $b = 0.5$ and optimize s_0 . At $\phi_v > 0$, the critical spacing depends much more on b than on s_0 , so we fix s_0 to the value estimated at $\phi_v = 0$ and optimize b . Note: ^aIndicates use of a triplet (three letters in a horizontal row) at 0.4 contrast rather than a quintuplet at 0.9 contrast.

In comparing our results and fits with those of Pelli et al., note that we used threshold criteria of 50% correct identification of letters and words. They used 80%. For letter identification, the higher criterion increases the critical spacing, which accounts for their higher estimate of normal s_0 (see Pelli et al., 2007; Figure 8). Corrected for guessing, this probability (criterion for letter identification) is the parameter P of the uncrowded span model. P affects the dither and thus shifts the model's curve (and critical spacing) along the log spacing axis. However, while the model does deal with the letter-identification criterion, the model does not explicitly refer to the performance criterion of the reading task. It simply assumes that the measured reading rate is proportional to the uncrowded span (Equation 1). One would expect the proportionality constant to depend on the criterion, but this would not affect the estimated critical spacing. For reading by human observers, lowering the threshold criterion (from their 80% to our 50%) increases reading rate but, remarkably, does not affect the critical spacing. This may be seen by comparing the Chung et al. (1998; Figures 3 and 7) reading rate curves for 80% and 50% threshold criteria.

In the Discussion section, we examine how critical spacing depends on eccentricity, finding that Bouma's law, $s = s_0 + b_1\varphi + b_2\varphi^2$ (Pelli et al.), though developed for normal vision, also fits our amblyopic results well.

Results

We set out to determine whether acuity or crowding limits amblyopic reading by comparing the critical sizes and spacings for identifying letters and reading words. We were confident that this would be revealing. However, the data surprised us. Not only do they answer the question of whether acuity and crowding matter but they also reveal what specific aspect of crowding limits reading.

Isolated and flanked letter acuities

Isolated and flanked letter acuities assess different aspects of visual function—size and spacing—but both are worsened by amblyopia and eccentricity, so we expected some correlation between them.

Figure 2 shows the effect of flankers on letter identification by plotting the flanked versus isolated letter acuity, for each eye and eccentricity. Flanked letter acuity is poorer than isolated letter acuity in every case: All the points lie above the dashed line of equality. This large effect of flankers on acuity is crowding.

The regression line (solid) has a log–log slope of 1.4, indicating that the two acuities are not proportional to each other. It is a power law with exponent 1.4. The ratio increases from 1.3:1 for the best acuities in central viewing to 5:1 in peripheral viewing. The ratio of flanked

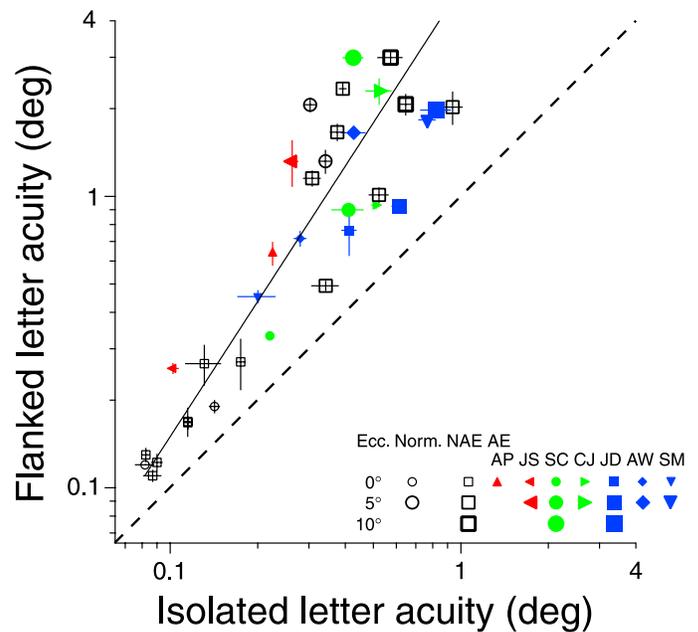


Figure 2. Letter acuity for flanked versus isolated letters. (“Flanked letter acuity”, here, is called “Critical spacing for crowding” in Figure 7, after applying a factor of $\times 1.1$ to convert size to spacing.) Acuity here represents the threshold letter size (50% correct). The dashed diagonal represents equality. The regression line is $y = (1.4 \pm 0.01)x + 0.64 \pm 0.07$ with $R^2 = 0.92$. Open symbols are for the preferred eyes of normal observers (circles) and the nonamblyopic eyes (NAE) of amblyopes (squares). Solid symbols are for the amblyopic eyes (AE). In this figure and in most of the figures that follow, symbol size indicates the eccentricity and color indicates the type of amblyopia: red for strabismic, green for anisometropic, and blue for those who are both strabismic and anisometropic.

to isolated acuity is about 3:1 for the fovea of the five amblyopes with strabismus (small red and blue symbols) and is nearly 2:1 (1.8:1 and 1.5:1) for the two anisometropes S.C. and C.J. (small green symbols). The flanked and unflanked acuities of untreated amblyopes reported by Tommila (1972) are practically the same as ours (Figure 2). Even higher ratios are evident in peripheral viewing (larger symbols).

Size or spacing?

Before presenting our reading results, we need to choose a horizontal scale. Is reading rate limited by size (acuity) or spacing (crowding)? Our reading tests covary size and spacing. For normal observers, Pelli et al. showed that reading is limited by crowding, and it is spacing, not size, that matters (also see Chung, 2002, 2004; Latham & Whitaker, 1996). Does this extend to amblyopes? For normals and amblyopes, we have just seen that flankers greatly increase the threshold size. To directly test the

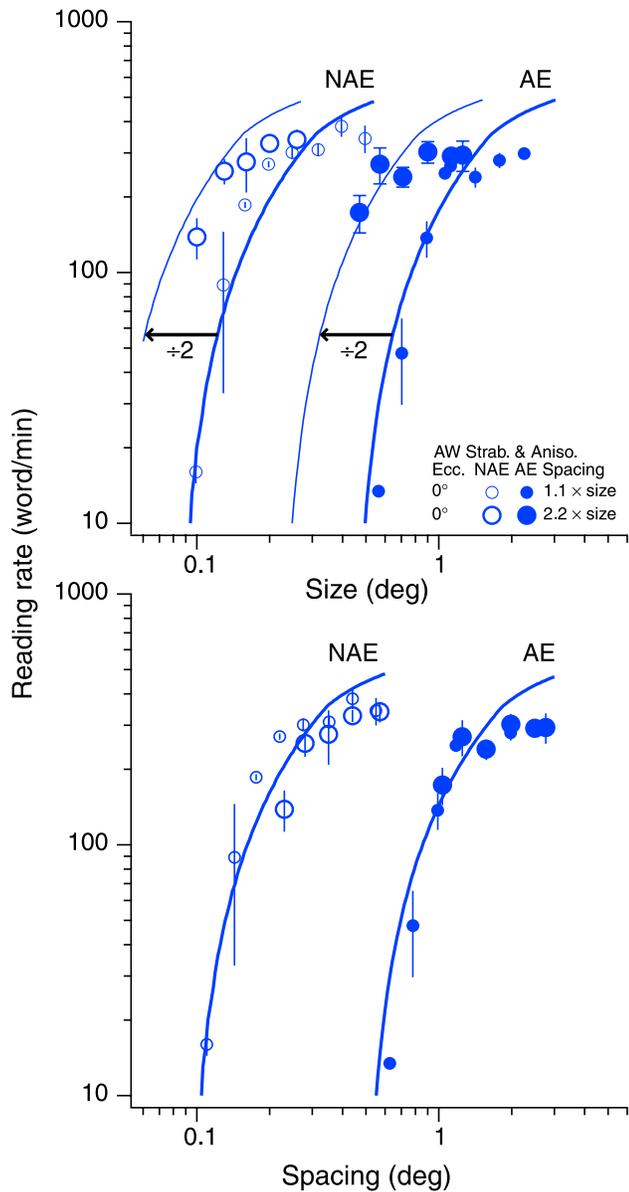


Figure 3. Reading rate versus size (top) and spacing (bottom) for each eye of an amblyope (strabismic and anisometric). The small symbols are for normal spacing (1.1 × size, these data also appear in Figure 4), and the large symbols are for double spacing (2.2 × size). The thick lines are the best fit of the uncrowded-span model (Pelli et al., 2007) to the normal-spacing data. The thin lines in the top graph are copies, shifted left (arrows) by a factor of 2, to predict the double-spacing data if spacing limits reading.

effect of spacing on amblyopic reading, we measured one observer’s reading performance with normal and doubled letter spacing (i.e., 1.1 and 2.2 times the letter size; Figure 3). In the size graph (top), doubling the spacing displaces the data a factor of 2 to the left, showing that spacing matters. In the spacing graph (bottom), doubling the size has no effect (both data sets lie on the same curve), showing that size does not matter. Thus, for this well-corrected observer reading normal and double-spaced text,

size does not matter and spacing does, so we plot reading rate versus spacing in all subsequent figures.

It may not be immediately apparent, but our finding (critical spacing dependent solely on eccentricity, independent of letter size) is entirely consistent with Chung’s (2002) measured effect of letter spacing on reading rate. She used a fixed letter size, so the letters overlapped at the smaller spacings that she used. Overlap produces ordinary masking, which slows reading. If we omit the cases of overlap, then her reading rates are

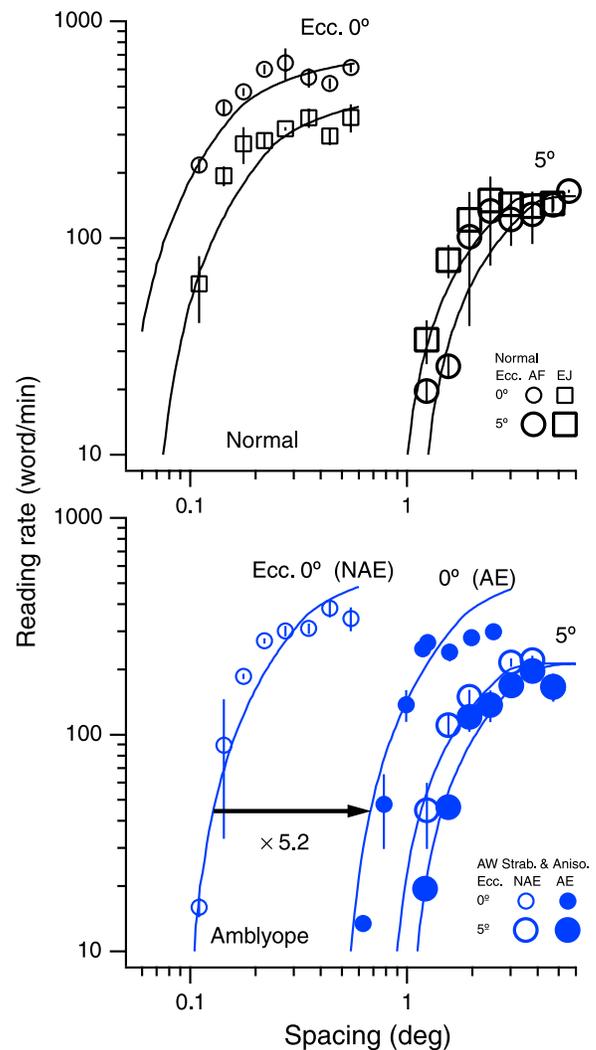


Figure 4. Reading rate versus spacing. (Top) Reading rate for two normal observers viewing centrally (small symbols) or at 5° in the lower visual field (large symbols). (Bottom) Reading rate for each eye of an amblyopic observer (A.W.) with both strabismus and anisometropia: nonamblyopic (open symbols) and amblyopic (solid symbols). The lines are the best fit of the uncrowded-span model (Pelli et al., 2007). The arrow shows the difference between the amblyope’s eyes, documenting the shift of the foveal reading curve to the right to larger spacing (ratio of AE to NAE). Table 2 presents the parameter estimates from the uncrowded-span fits and, for comparison, the results of two-line fits (see Methods).

independent of spacing, indicating that the critical spacing for crowding was smaller than the smallest spacing that she could present without overlap. Yu, Cheung, Legge, & Chung (2007) used the same paradigm and similar comments apply.

Reading

Reading rate increases rapidly with print size and then, beyond the critical print size, asymptotes to a maximum reading rate. Chung et al. (1998) show that the curve measured in the normal periphery is similar in shape to that measured centrally but is shifted to the right (larger print sizes) and down (slower maximum reading rates). Figure 4 (top) replicates their result in two normal observers.

Figure 4 (bottom) compares the amblyopic and non-amblyopic eyes of one amblyope, showing that in amblyopic central vision, as in the normal periphery, the curve is shifted rightward, as indicated by the arrow. However, unlike the peripheral reading rate, the maximum

central reading rate is practically the same in the two eyes. For this amblyopic eye, the curve for central vision is shifted to the right by a factor of 5.2, whereas the peripheral curve is hardly affected by amblyopia.

The results for the other six amblyopes are similar (Figure 5). For every amblyope, central reading with the amblyopic eye is a rightward-shifted version of the nonamblyopic-eye curve. Among the seven amblyopes (Figures 4 and 5), the shift ranges from $\times 2$ to $\times 13$, with a median of $\times 3$. For all seven amblyopes, once the spacing is sufficiently large, central reading rate is practically the same in the two eyes. Because print size and spacing covary in this experiment, another way to state this is that once the print is large enough to read, the central reading rate is practically the same in the two eyes of amblyopes.

Peripheral reading rate (5° or 10° in the lower field) is practically the same in the two eyes over the entire range of letter spacings.

Note that the roughly threefold increase in critical spacing is relative to the nonamblyopic eye, which is not normal. Critical spacing in the nonamblyopic eyes is about twice normal.

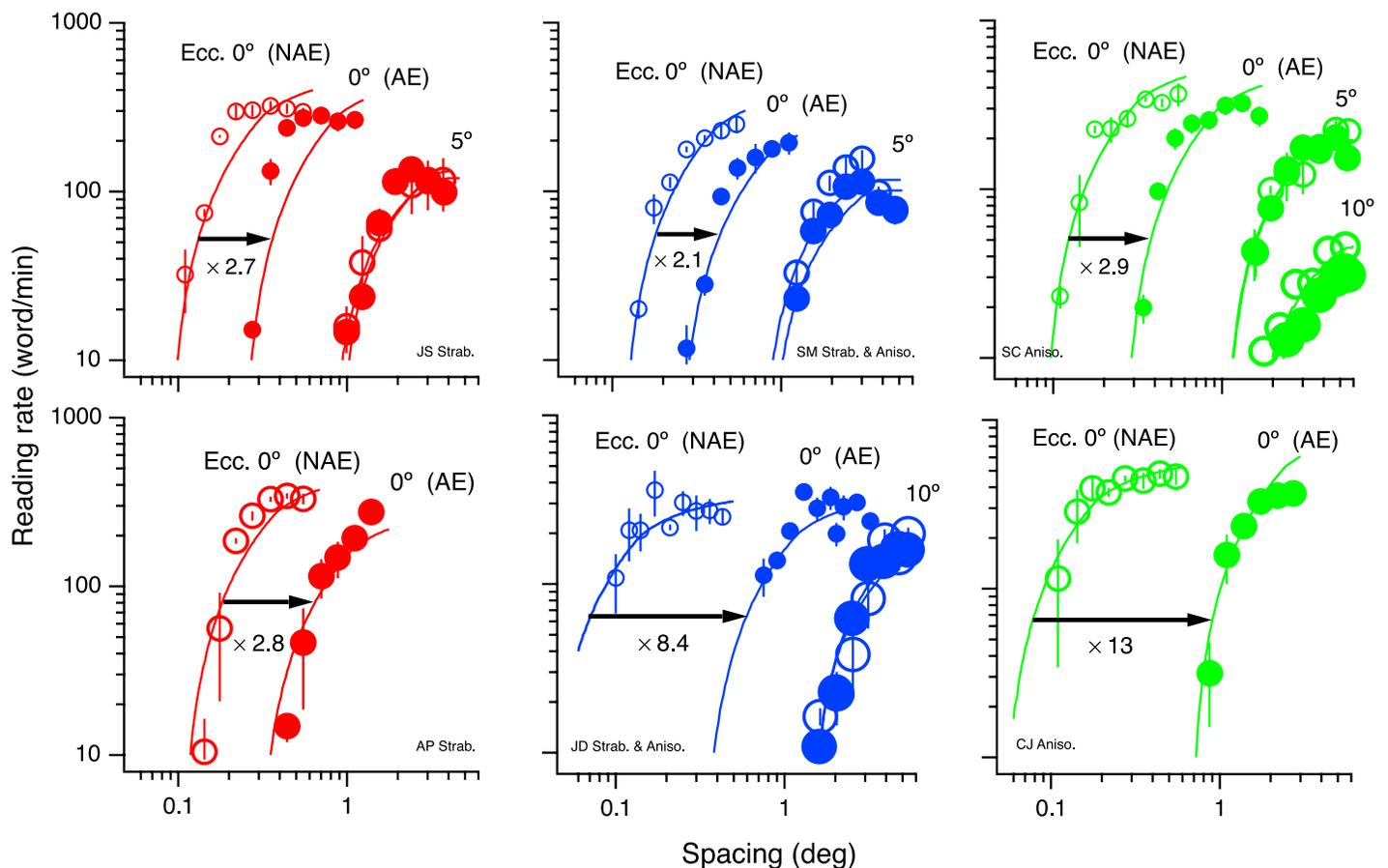


Figure 5. Reading rate versus spacing: six amblyopes. Threshold reading rate is plotted against spacing ($1.1 \times$ size) for each eye of six amblyopic observers. Other details are as described in Figure 4. In all our figures, color indicates amblyopic etiology: red for strabismic, green for anisometric, and blue for those who are both strabismic and anisometric.

Maximum reading rate versus critical spacing

For each amblyopic eye, once the letter spacing exceeds the critical spacing for reading, performance becomes independent of letter spacing and attains the same maximum reading rate as the fellow dominant eye (Figures 4 and 5).

The reading rate curve has a characteristic shape and varies (with eccentricity and other conditions) mostly by shifting position in the log reading rate versus log spacing coordinate frame. Thus, the position of the curve in each condition is a useful summary of the results. Fitting the uncrowded-span model is like fitting Chung's two-line fit (see Methods) in that both fit the data reasonably well and yield a two-number summary, corresponding, more or less, to the best x and y position of a template curve.

Previous authors have used the critical print size and maximum reading rate provided by the two-line fit (Chung et al., 1998). We use critical spacing for reading instead of critical print size, partly because we are specifically interested in the uncrowded-span model, which provides this parameter and partly because we think that it is misleading to talk about size, which we now know to be irrelevant, instead of spacing. Table 2 provides estimates of the critical print size for reading provided by the two-line fit of Chung et al. (1998), and we note that the critical print size is about 1.5 times the critical spacing for reading, which is 1.1 times the acuity for flanked letters (Table 2).

With no assumptions, the two-line fit has no theory, so the numbers are just numbers, with no link to crowding. The uncrowded-span model predicts reading rate from critical spacing, so fitting that model estimates the critical spacing of crowding that would account for the reading rate data. If the model is right, its estimate should agree with direct measurement of the critical spacing.

Figure 6 plots the maximum reading rate against critical spacing for reading for each observer. Amblyopia has no effect on one parameter (vertical scale) and affects the other (horizontal scale) only at 0° (left panel). With central viewing (left panel), the maximum reading rates for most (6/7) of the amblyopic eyes (solid symbols) fall within the 95% confidence interval for central reading by nonamblyopic eyes (gray bar). The fastest amblyopic eye (C.J.'s) sails above the rest, including all the normal and nonamblyopic eyes. In contrast, all of the peripheral data (normal, nonamblyopic, and amblyopic eye—right panel) fall far below the 95% confidence interval for central reading, mostly clustering around 200 words/min.

In light of the many suggestions that the normal periphery is a good model for the amblyopic fovea, we were surprised by this striking difference between amblyopic central reading (colored symbols in the left panel) and normal peripheral reading (open circles in the right panel). Relative to normal central reading, critical spacing is greatly increased both in the periphery and by amblyopia. However, the maximum reading rate is greatly reduced in the periphery but unaffected by amblyopia.

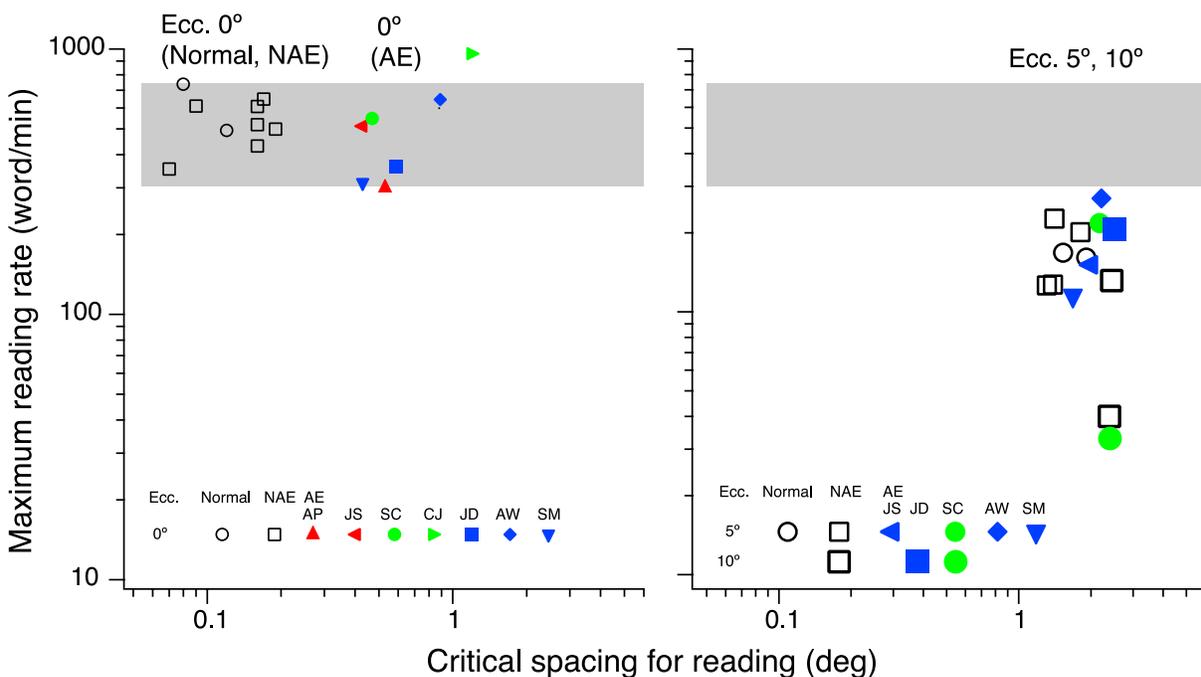


Figure 6. Maximum reading rate (derived from the fits to the reading data in Figures 4 and 5) is plotted as a function of critical spacing for reading. (Left) Central reading. (Right) Peripheral reading. The gray bar is the 95% confidence interval for the nonamblyopic eyes reading centrally. Other details are as described in Figure 4.

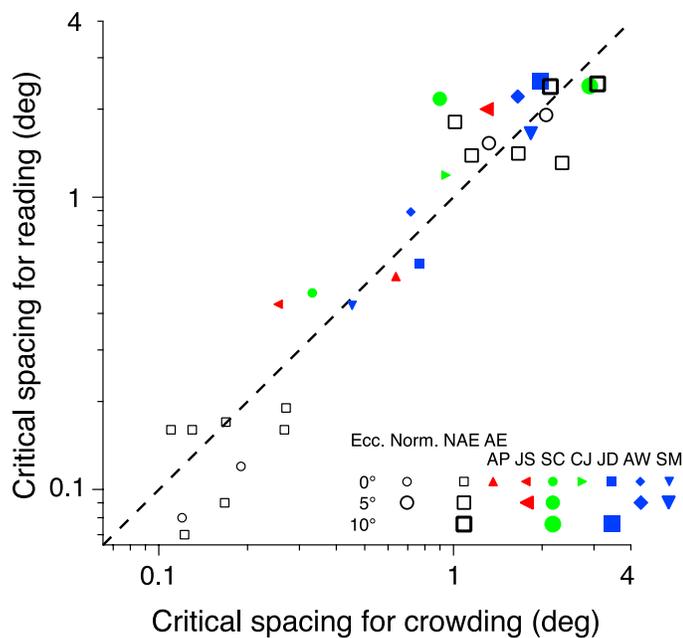


Figure 7. Critical spacing for reading as a function of critical spacing for crowding (called “flanked letter acuity” in Figure 2). The dashed diagonal represents equality. Estimates of the critical spacing for reading were derived from the fits to the reading data (Figures 4 and 5) for the amblyopic (solid symbols), nonamblyopic (open squares), and normal (open circles) eyes. Amblyopia type is coded by color; eccentricity is coded by symbol size. For each point, the 95% confidence interval is approximately the size of the large symbols. The regression line (not shown) is $y = (1.04 \pm 0.06)x + 0.00 \pm 0.03$ with $R^2 = .96$, which is consistent with equality $y = x$.

This unanticipated amblyopic result turns out to be an unavoidable prediction of the uncrowded span theory (Equation 1) and provides a crucial affirmation of it, as we will explain in the Discussion section.

Figure 6 reveals the surprising simplicity of our results. Amblyopia has a big effect on the critical spacing of central reading, but that is all. Amblyopia spares critical spacing of peripheral reading and spares maximum reading rate everywhere. In the amblyopic eye, critical spacing of central reading is increased from normal by a factor of 5 (ratio of geometric means) and there is no overlap of the two groups. In the nonamblyopic eye, critical spacing of central reading is increased from normal by a factor of 2.

Reading words versus identifying a letter

We find that the critical spacing for reading equals the critical spacing for crowding (Figure 7). We plot the critical spacing for reading against both flanked (Figure 7) and isolated (Figure 8) letter acuity. In Figure 7, the data fall close to the line of equality. Within the error of measurement, under all conditions, over a wide 30:1 range, the critical spacing for reading is equal to the critical

spacing for crowding. Averaged across the various eyes and eccentricities, the ratio of the two measures is 1.00 ± 0.03 . They are equal. As demanded by equality, the regression equation (see Figure 7 caption) has a slope of 1 and an intercept of 0. Given the equality of the two kinds of critical spacing, it is not surprising that both measures have a similar association with acuity (Figures 2 and 8). The unique association (equality) with spacing (Figure 7) and the more arbitrary association (power law) with size (Figure 8) suggest that reading is limited by spacing, not size.

We are impressed by the robustness of the equality across this diverse set of observers, eyes, and eccentricities. However, one can still ask whether the equality of these two measures across our whole diverse sample of eyes and eccentricities is also present within a subset. In particular, does the result still hold if we look at only one eccentricity? For this test, we need a group that spans a range, so we examine the amblyopic eyes at 0° , for which the critical spacing for reading has a range of 3:1. A linear regression restricted to those seven points yields $y = (1.0 \pm 0.3)x + 0.1 \pm 0.2$ with $R^2 = 0.85$. Again, the slope is 1 and the intercept is 0. This is the same result—equality—that we saw in the full data set.

The corresponding regression equations for log critical spacing for reading (which is proportional to critical print size) as a function of log critical size (i.e., isolated acuity, Figure 8) have a slope of 1.5 ± 0.1 for the full data set and a slope of 0.8 ± 0.2 for the seven amblyopic eyes at 0° . These two slopes disagree with each other. One could suppose a nonlinear dependence of critical spacing for

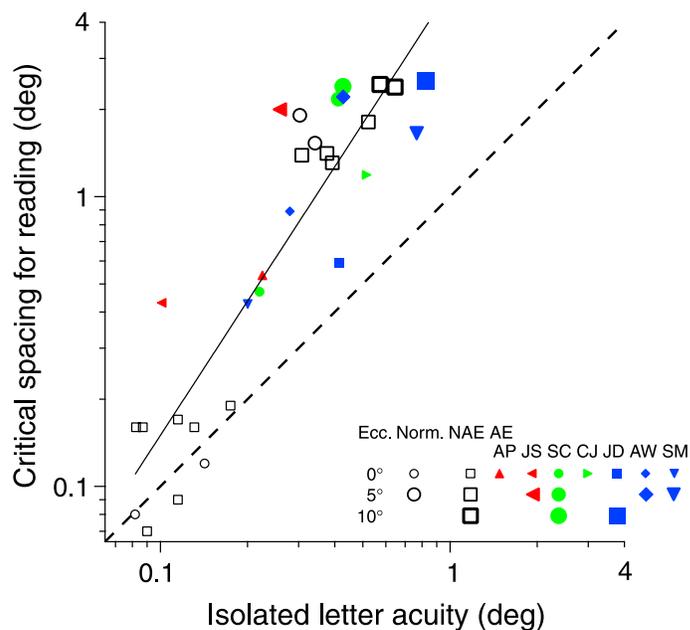


Figure 8. Critical spacing for reading as a function of the isolated letter acuity. The dashed diagonal represents equality. The regression line (solid) is $y = (1.50 \pm 0.13)x + 0.69 \pm 0.09$ with $R^2 = 0.91$. Other details are as described in Figure 7.

reading (or critical print size) on acuity, but it is hard to imagine how one would account for two different power law exponents: expansive ($1.5 > 1$) overall but compressive ($0.8 < 1$) within this group (amblyopes at 0°). Thus, the crowding story—equality—is as simple as could be, whereas an acuity-based account seems unworkable.

We have been arguing that the critical spacing (and critical print size) for reading are consequences of critical spacing, not acuity. Our regression analysis of Figure 8 shows that restricting the range of eccentricities reduces the exponent relating critical spacing to acuity, which seems to undermine any claim that one causes the other. But, if we deny a causal link between critical spacing and acuity, then why are they correlated ($R^2 = 0.9$ in Figures 2 and 8)? Common cause. It has long been known that acuity and critical spacing depend on eccentricity, so it is no surprise that they are correlated in a data set that includes a range of eccentricities. The eccentricity dependence of both suggests that critical spacing and acuity might be independent effects of a common eccentricity-dependent factor (e.g., in the development of the retina).

Assumption-free confirmation

When we first posed the size-or-spacing question, in the Introduction, we noted that one could simply measure and compare, without assuming anything. The two-line fit provides the critical print size without the baggage of assuming any model. The regression of log critical print size (CPS) against log flanked acuity is $y = (1.01 \pm 0.06)x + 0.16 \pm 0.03$ with $R^2 = 0.96$ and the regression of log CPS against log isolated acuity is $y = (1.48 \pm 0.12)x + 0.84 \pm 0.08$ with $R^2 = 0.92$. These regression lines (not shown) have practically the same slopes as the regression lines for the critical spacing for reading (Figures 7 and 8). Again, the relation with flanked acuity has a slope (1) consistent with equality or proportionality, and the relation with isolated letter acuity has a much greater slope ($1.5 > 1$). The weakness of this assumption-free test is that it only tests the slope of the regression line (1 for equality), not the intercept (0 for equality). The intercept (0.16 ± 0.03) is the log ratio of the CPS to flanker acuity. It depends on the criterion for letter identification, increasing threefold over a criterion range of 0.3 to 0.9 (Pelli et al., 2007; Figure 8). Thus, this test is not as stringent as the model-based one, because it tests only the slope, not the intercept, of the regression line. Even so, it confirms our equality result without assuming any model.

Discussion

The results indicate that the amblyopic impairment of reading is simply a consequence of the increased crowd-

ing in amblyopia. Thus, amblyopes read normally except that abnormal crowding in the fovea prevents them from reading fine print. Critical spacing in the nonamblyopic eye is roughly twice the normal and in the amblyopic eye is five times the normal. Abnormally increased crowding in the fovea of the preferred eyes of amblyopes was first noted for Vernier acuity (Levi & Klein, 1985). Our results confirm and extend the study of Pelli et al. (2007) from normal vision to amblyopia. The normal model fits the amblyopic results well, with a roughly fivefold increase in critical spacing at fixation and no change in the larger critical spacings found more peripherally. Finally, it turns out that the case of amblyopia provides a stringent test of the hypothesis that the effect of crowding on reading is mediated by the uncrowded span.

The conclusion that reading rate is limited by crowding is based on Figure 7, the equal critical spacing for two different tasks: identifying a flanked letter and reading a stream of words. This makes sense if we suppose that reading is mediated by letter identification and that letter identification is limited by crowding. Otherwise, the equality found in Figure 7 seems an improbable coincidence.

Many aspects of vision worsen gradually with eccentricity or amblyopic severity, but it seems likely that most are secondary consequences of worsened acuity and crowding. Acuity and critical spacing assess different aspects of visual function. As expected, we find that in well-corrected amblyopes, the flanked acuity (i.e., critical spacing) is worse than the isolated letter acuity. Moreover,

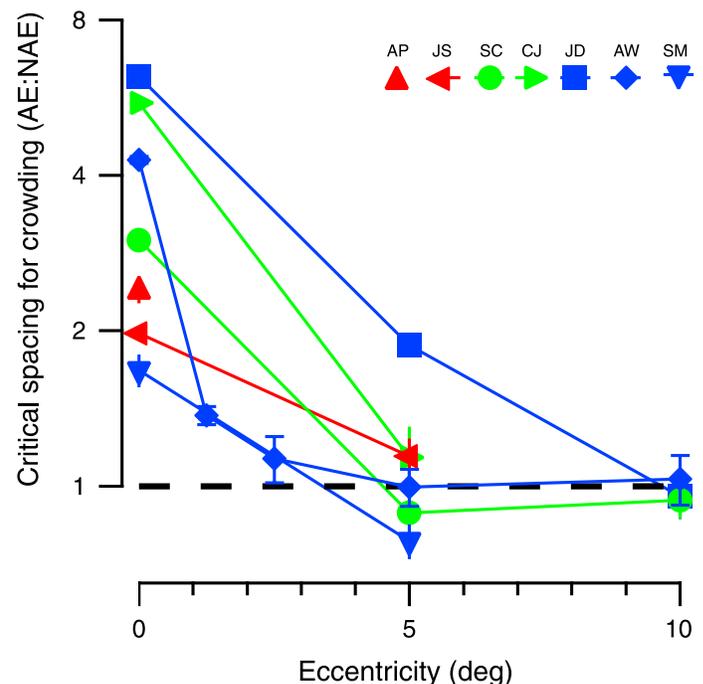


Figure 9. Critical spacing ratio (i.e., amblyopic:nonamblyopic ratio of the flanked letter acuity) as a function of eccentricity. Data are from Figure 2.

we note that the ratio of the two acuities has a wide range, from 1.3:1 to 5:1 (Figure 2). If the flanked acuity were a fixed multiple of isolated letter acuity, one might think that they were linked. Instead, the variable ratio suggests that they are independent, and it is the flanked acuity that limits reading performance. The association between reading and acuity (nonlinear and inconsistent between the amblyopic group at 0° and the whole set of observers at 0° to 10°) shown in Figure 8 is much less compelling than the equality revealed in Figure 7.

How crowding limits reading

The central field of amblyopes is similar to the normal periphery in many respects (e.g., Levi, 1991; Levi & Klein, 1985, Levi et al., 1985; Levi et al., 1994a, 1994b, but see Levi et al., 2002a). The similarity suggests that amblyopia (or at least some aspects of amblyopia) might be explained on the basis of an “equivalent eccentricity”, that is, an eccentricity in the normal periphery where performance is equivalent to that of the amblyopic fovea.

The amblyopic deficit in our results is strictly central. Our results show that amblyopia greatly increases the minimum critical spacing (flanked letter acuity) in the central visual field but spares the larger critical spacings found more peripherally. Figure 9 replots the data from Figure 2 to show the amblyopic:nonamblyopic ratio for each amblyope as a function of eccentricity. At 0°, the ratio is large, ranging from 2:1 to 6:1, with a median of 3:1. The ratio is about 1:1 at 5° for all but one (J.D.) of the six observers and is about 1:1 at 10° for all three observers we tested at that eccentricity, including J.D.

Uncrowded span

“Uncrowded span” is the number of character positions in a line of text with a given spacing and vertical eccentricity that are uncrowded, that is, spaced apart more than the critical spacing (Pelli et al., 2007). The uncrowded-span model of reading rate supposes that reading rate is proportional to the uncrowded span and that the uncrowded span is determined by critical spacing (Bouma, 1970; Legge et al., 2001; Pelli et al., 2007). How, then, can it be that amblyopia greatly increases the critical spacing at 0° yet has no effect on maximum reading rate (Figure 6)?

The case of amblyopia reveals that crowding limits reading solely by determining the uncrowded span. Letters in text may be uniformly spaced, but the observer’s critical spacing increases out from fixation (Figure 10), so the uncrowded region extends out to where the spacing is critical. Letters inside the region have more-than-critical spacing and letters outside the region have less-than-critical spacing. Amblyopes have normal critical spacing in the periphery, so, when the uncrowded region extends into the periphery, its span is normal, which predicts our finding that reading rate is normal too. This confirms the

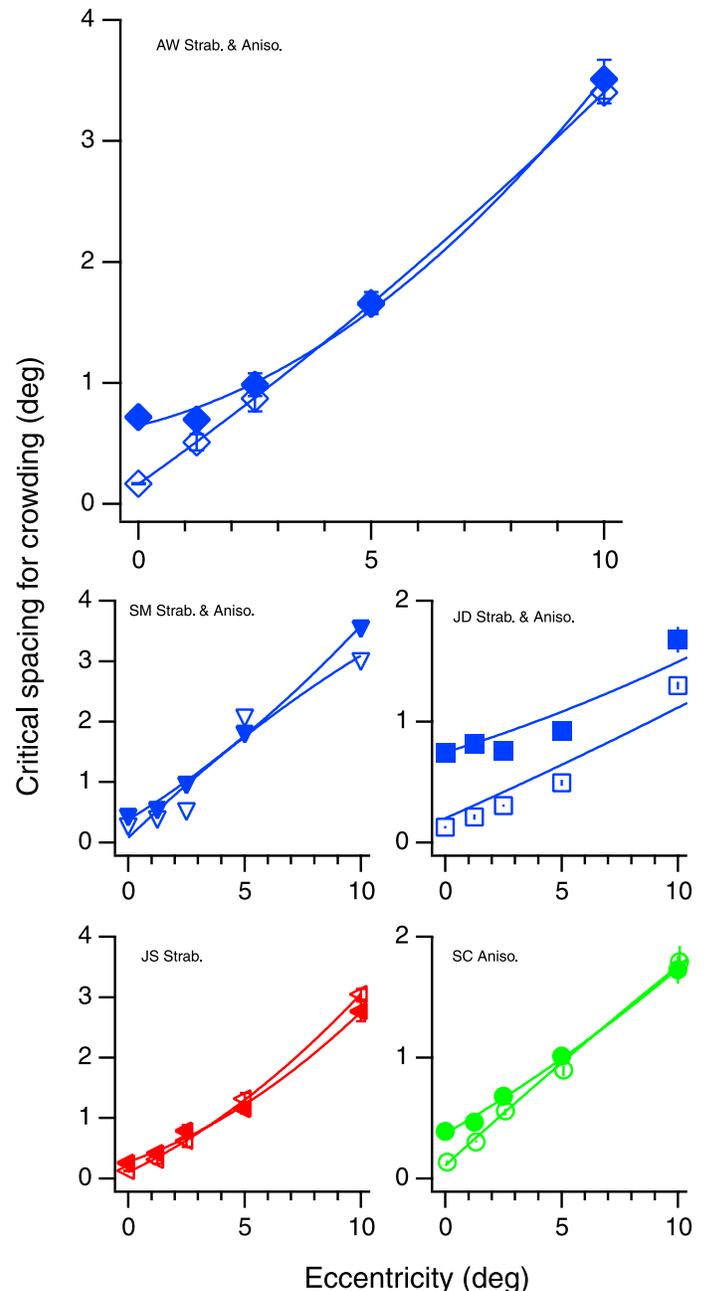


Figure 10. Critical spacing for both eyes of five amblyopes, as a function of eccentricity on the vertical midline in the lower visual field. The data for each eye are fit by the generalized Bouma’s law, $s = s_0 + b_1\phi + b_2\phi^2$ (Pelli et al., 2007; Equations 1 and 2). Note that for A.W., S.M., and J.S., the data are quintuplet acuity at $c = 0.9$ (the standard condition), whereas for J.D. and S.C., we show acuity with horizontal triplets at $c = 0.4$, which halves the critical spacing.

theory that reading rate is determined by the span of the uncrowded region, independent of the critical spacing within the region.

Consider amblyopic observer A.W. She achieves maximum reading rate at a spacing of about 1.5° (Figure 4). Her maximum reading rate is normal, so we expect that her

uncrowded span will also be normal. The normal uncrowded span for central reading at maximum reading rate is about six characters, that is, three characters on either side of fixation, if, for convenience, we assume symmetry. At this 1.5° spacing, the most peripheral of the six characters in A.W.'s uncrowded span will be at eccentricities of -3.75° and $+3.75^\circ$. Figure 10 shows her critical spacing as a function of eccentricity. Amblyopia sets a floor, raising the minimum critical spacing centrally without affecting higher values more peripherally. Interpolating between points, Figure 10 suggests that A.W.'s critical spacing at 3.75° is normal (i.e., identical in her amblyopic and nonamblyopic eyes). The normal critical spacing accounts for the normal uncrowded span, which, in turn, accounts for her normal reading rate.

Figure 10 includes comparable graphs for four more amblyopes. As we noted in Figure 9, they all conform to the same pattern. Centrally, the critical spacing is roughly threefold higher in the amblyopic eye than in the nonamblyopic eye, varying among observers, but this elevation disappears peripherally as the ratio drops to 1:1.

To recap, amblyopia hurts the fovea and spares the periphery. For central reading, the critical spacing for reading is determined by the ability to see one character in the fovea and is much affected by amblyopia. The maximum reading rate is determined by the uncrowded span, which is constrained by its extremities, which fall in peripheral retina, which is unaffected by amblyopia. Thus, the critical spacing for reading is impaired (as is the fovea), yet the maximum reading rate is unscathed (as is the periphery).

Our finding that maximum reading rate is unaffected by amblyopia confirms the uncrowded-span theory that (at any given eccentricity) reading rate is determined by the width of the uncrowded region, the number of letters in the span, independent of the critical spacing within.

Amblyopia as arrested development

The amblyopic fovea is immature in many ways (Levi & Carkeet, 1993). The large critical spacing for reading in the amblyopic fovea may reflect a failure of the amblyopic visual system to follow the normal developmental reduction. If the periphery is a guide, this is more than just a matter of having enough practice. Practice can substantially improve peripheral reading, but even after this perceptual learning, peripheral reading remains slow (Chung, Legge, & Cheung, 2004). The normal visual span increases during childhood (Kwon & Legge, 2006), and, at least in adults, the visual span is the uncrowded span, which is inversely related to the critical spacing (Pelli et al., 2007). Three-to-six-year olds have more foveal crowding than adults (Atkinson et al. 1988). Thus, as far as reading is concerned, the amblyopic deficit could be just a failure of the foveal critical spacing for crowding to shrink from childhood to normal adult size.

Conclusion

Crowding limits reading. For well-corrected observers, whether vision is normal or amblyopic, central or peripheral, the critical spacing for reading equals the critical spacing for crowding.

The amblyopic deficit in reading is fully accounted for by crowding. The critical spacing at fixation is five times larger in amblyopic eyes than in normal eyes. Amblyopic reading rate is normal at larger-than-critical spacings and drops precipitously, to a crawl, at smaller-than-critical spacings.

The uncrowded-span model of reading rate in normal vision fits the amblyopic results well, with a roughly fivefold increase in the critical spacing at fixation and no change in the larger critical spacings found more peripherally. The increase is twofold in the nonamblyopic eye.

The effect of crowding on reading rate is wholly mediated by the uncrowded span. The left and right boundaries of the uncrowded span are out where the spacing is critical. Our results, comparing reading by amblyopic and nonamblyopic eyes, show that only the span matters. The threefold increase of the critical spacing within the uncrowded span has no effect on reading rate. Reading rate is determined by the width of the uncrowded span, independent of the critical spacing within the span.

This report consistently distinguishes the critical spacing for reading from that for identifying a letter (“crowding”), finding that they are equal. In future writings, those who accept our demonstration that they are just two ways of measuring the same thing might simply refer to “critical spacing” and leave the details of measurement to their Methods section.

Acknowledgments

This is the fifth in a series of papers about crowding and its cure (#1 Pelli et al., 2004; #2 Martelli, Majaj, & Pelli, 2005; #3 Pelli & Tillman, 2007; #4 Pelli et al., 2007, this issue; #6 Freeman & Pelli, 2007, this issue). This study was supported by research grants RO1EY01728 and RO1EY04432 from the National Eye Institute, NIH, to D.M.L. and D.G.P. Thanks to Katharine Tillman, Susana Chung, Gordon Legge, Roger Li, Marsha Meytlis, Jamie Radner, and Hans Strasburger for insightful comments. Many thanks to Gordon Legge for suggesting the double-spacing experiment (Figure 3).

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