

# Crowding and eccentricity determine reading rate

**Denis G. Pelli**

Psychology and Neural Science, New York University,  
New York, NY, USA



**Katharine A. Tillman**

Psychology and Neural Science, New York University,  
New York, NY, USA



**Jeremy Freeman**

Swarthmore College, Swarthmore, PA, USA



**Michael Su**

Psychology and Neural Science, New York University,  
New York, NY, USA



**Tracey D. Berger**

Psychology and Neural Science, New York University,  
New York, NY, USA



**Najib J. Majaj**

Psychology and Neural Science, New York University,  
New York, NY, USA



Bouma's law of crowding predicts an uncrowded central window through which we can read and a crowded periphery through which we cannot. The old discovery that readers make several fixations per second, rather than a continuous sweep across the text, suggests that reading is limited by the number of letters that can be acquired in one fixation, without moving one's eyes. That "visual span" has been measured in various ways, but remains unexplained. Here we show (1) that the visual span is simply the number of characters that are not crowded and (2) that, at each vertical eccentricity, reading rate is proportional to the uncrowded span. We measure rapid serial visual presentation (RSVP) reading rate for text, in both original and scrambled word order, as a function of size and spacing at central and peripheral locations. As text size increases, reading rate rises abruptly from zero to maximum rate. This classic reading rate curve consists of a cliff and a plateau, characterized by two parameters, critical print size and maximum reading rate. Joining two ideas from the literature explains the whole curve. These ideas are Bouma's law of crowding and Legge's conjecture that reading rate is proportional to visual span. We show that Legge's visual span is the uncrowded span predicted by Bouma's law. This result joins Bouma and Legge to explain reading rate's dependence on letter size and spacing. Well-corrected fluent observers reading ordinary text with adequate light are limited by letter spacing (crowding), not size (acuity). More generally, it seems that this account holds true, independent of size, contrast, and luminance, provided only that text contrast is at least four times the threshold contrast for an isolated letter. For any given spacing, there is a central uncrowded span through which we read. This uncrowded span model explains the shape of the reading rate curve. We test the model in several ways. We use a "silent substitution" technique to measure the uncrowded span during reading. These substitutions spoil letter identification but are undetectable when the letters are crowded. Critical spacing is the smallest distance between letters that avoids crowding. We find that the critical spacing for letter identification predicts both the critical spacing and the span for reading. Thus, crowding predicts the parameters that characterize both the cliff and the plateau of the reading rate curve. Previous studies have found worrisome differences across observers and laboratories in the measured peripheral reading rates for ordinary text, which may reflect differences in print exposure, but we find that reading rate is much more consistent when word order is scrambled. In all conditions tested—all sizes and spacings, central and peripheral, ordered and scrambled—reading is limited by crowding. For each observer, at each vertical eccentricity, reading rate is proportional to the uncrowded span.

**Keywords:** crowding, critical spacing, uncrowded window, reading, periphery, context gain, RSVP, print exposure, word order, cue combination, object recognition, isolation field, uncrowded span, visual span, letter substitution, critical print size, CPS

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## Modeling reading rate

### The reading rate curve

Reading matters, and understanding reading rate is crucial to theories of reading and how to teach it (Coltheart, Rastle,

Perry, Langdon, & Ziegler, 2001; Engbert, Nuthmann, Richter, & Kliegl, 2005; Legge, 2007; O'Regan, 1990; Rayner, Foorman, Perfetti, Pesetsky, & Seidenberg, 2002; Reichle, Rayner, & Pollatsek, 2003; Stanovich, 2000). As text size increases, reading rate rises abruptly from zero to maximum rate (Fig. 1). Beyond this *critical print size* (CPS), reading rate is nearly flat, independent of letter size.

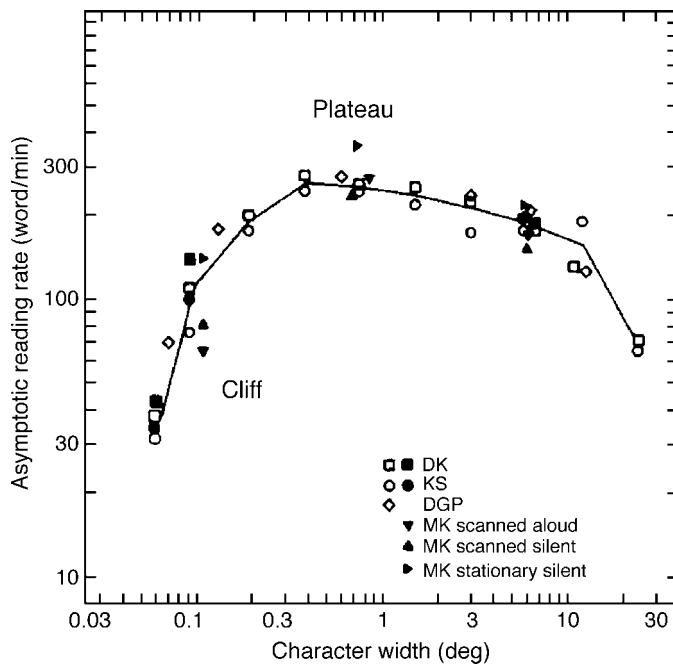


Figure 1. The classic reading rate curve (Legge, Pelli, Rubin, & Schleske, 1985, with added labels). The range of size is 400:1, from 0.06° to 24°. This graph, or one like it, can be used to select the print size for optimal reading rate. The droop of the plateau at large sizes is an expected consequence of perspective compression at extreme viewing angles (Appendix B). Legge et al. defined “width” as spacing. For their uniformly spaced Elite font, the center-to-center letter spacing is 0.93 times x-height. 1 word/min is 0.1 character/s.

The curve finally descends due to perspective compression at large visual angles. The critical print size and maximum reading rate depend on the viewing conditions, but the curve shape—steep cliff and wide plateau—is universal for central, peripheral, static, and rapid serial visual presentation. This basic result is well established but unexplained.

Acuity and several other kinds of visual resolution are proportional to eccentricity, i.e., the distance from fixation (Virsu & Rovamo, 1979; Wilson, Levi, Maffei, Rovamo, & DeValois, 1990). Such limits are scale-invariant: Scaling size and eccentricity together, e.g., by changing viewing distance, will not affect performance. If such a limit applies to reading, reading rate will be independent of print size, since size and spacing covary (Legge, Mansfield, & Chung, 2001; O’Regan, 1990). Thus, the plateau indicates a scale-invariant limitation. This insight is helpful, but falls short of explaining what limits reading rate. For example, it does not distinguish between crowding and acuity as possible limits.

It has long been known that reading consists of four fixations per second, suggesting that reading is limited by the number of letters acquired in each fixation. That span has been measured in various ways, but remains unexplained.

Here we prove that, under ordinary conditions (well-corrected fluent observers reading ordinary text with adequate light), the “visual span” is simply the number of characters that are not crowded.

This two-part narrative—modeling and proof—presents each idea and result as soon as the necessary infrastructure is in place to support it. (Methods appear at the end.) First, we show that the “visual span” is the “uncrowded span,” establishing a strong link between reading and crowding. With this glue, we then join two ideas from the literature—Bouma’s law of crowding and Legge’s conjecture about reading—to create a hybrid theory that accurately predicts the shape of the reading rate curve. Finally, to prove it, we show that crowding determines the positions of the cliff (critical print size) and the plateau (maximum reading rate). Thus, we show that—at all letter sizes and spacings, at all eccentricities—reading is limited by crowding.

A sister study, in this issue, presents similar results for amblyopic vision, showing that the amblyopic deficit in reading is entirely accounted for by crowding (Levi, Song, & Pelli, 2007).

## Crowding

In the periphery, it is hard to identify a letter that is surrounded by other letters (Fig. 2). This phenomenon is called *crowding* (Stuart & Burian, 1962). Crowding is excessive feature integration, inappropriately including extra features that spoil recognition of the target object. An early preattentive bottleneck in the object recognition process, crowding is characterized by a critical spacing that depends on eccentricity (distance from fixation) and little else. Critical spacing is the smallest distance between letters (center-to-center) that avoids crowding. We have previously studied the effects of crowding on identification of single letters, words, and faces (Martelli, Majaj, & Pelli, 2005; Pelli, Palomares, & Majaj, 2004). Here we examine reading, focusing on the identification of words in the context of a sentence. The sentence context normally helps in identifying each word but can be abolished by scrambling the word order, revealing unexpectedly high consistency among observers (Appendix D).

Words are recognized by parts. The letters are recognized independently but crowd each other (impairing identification of the word) unless they are separated by

r + are

Figure 2. Crowding. Fixate the large +. It is easy to identify the r on the left but impossible to identify the r on the right. The flankers, “a” and “e,” spoil recognition of the target. Fixating the small +, it is easy to identify the r on the right. Reducing the eccentricity of the target reduces your critical spacing, which relieves crowding.

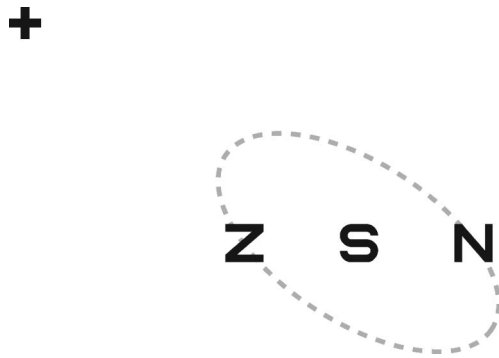


Figure 3. Measuring critical spacing. The observer fixates the +. On successive trials, the spacing of the letters is varied to discover what spacing is required for 80% correct identification of the target (middle) letter. The ellipse represents critical spacing measured at every orientation of flanker position relative to the target (see Fig. 6).

at least the critical spacing (Bouma, 1973). Figure 2 demonstrates crowding. The critical spacing for crowding defines an *isolation field*, a region over which the visual system integrates features (Fig. 3). The isolation field defined by the critical spacing is the smallest isolation field at that location. We suppose that isolation fields larger than this are also available at that location and are used to identify larger letters. We have wondered whether there is a maximum isolation field size and what consequences this might have, but that is not relevant here. Our experiments keep our observers at the threshold spacing for letter identification, so they are always using their smallest available isolation field. The minimum isolation field size increases with eccentricity, but is independent of target size (and type, Martelli et al., 2005).

In the periphery, unless object spacing is sufficient, more than one object will fall in the same isolation field, spoiling recognition (Fig. 4). One would expect this to make peripheral reading very difficult, if not impossible, unless the letter spacing is huge. Indeed, peripheral reading is much slower than central reading (e.g., 150 word/min, one third the foveal rate, at 10° in the periphery). However, to everyone's surprise, reading rate is practically independent of letter spacing, provided the letters do not overlap (Chung, 2002; Legge, Pelli, Rubin, & Schleske, 1985; also see Fig. 11, below). Increasing the spacing does not make peripheral reading faster, which might seem to suggest that crowding cannot be the limit. How could crowding limit word recognition but not reading? Our analysis resolves this seeming paradox.

## RSVP and peripheral reading

Peripheral reading is vital to people with central field loss, which is common in the elderly (Leibowitz et al., 1980). Factors that might limit peripheral reading rate include acuity, eye movements, and crowding. It is hard to

make the right eye movements for peripheral reading, but the need for eye movements can be minimized by presenting words one at a time in rapid serial visual presentation, RSVP (Potter, 1984; Rubin & Turano, 1992). Despite much effort, there is still no explanation for why reading is slower at greater eccentricity (Battista, Kalloniatis, & Metha, 2005; Falkenberg, Rubin, & Bex, 2007). We return to this in the Discussion section.

## Comparing laboratories

There is great interest in the effect of eccentricity on reading, partly because people who must read peripherally due to central field loss complain about how slow it is, and partly because accounting for the effect of eccentricity on reading rate seems a good test of reading theories. However, various studies have reported widely different rates, dimming hope that peripheral reading will be explained soon (Fine, Hazel, Petre, & Rubin, 1999). In Appendix D, we compare reading of ordered and unordered text. We find that results differ in only one parameter, maximum rate, and that the maximum rate, for both central and peripheral reading, is much less variable across observers in the unordered than in the ordered conditions. Thus, we are happy to report that unordered reading rates reveal an unexpectedly high consistency among observers and laboratories.

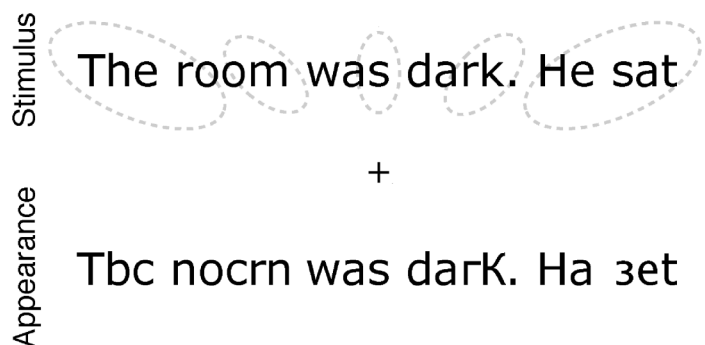


Figure 4. What does crowding look like? The + in the middle is a fixation mark. The top line is a stimulus (with a few isolation fields drawn in faintly). The bottom line is a simulation of its appearance to an observer fixating the +. An isolation field must contain only one letter in order to identify it. When isolation fails, features from several letters are integrated and recognition fails, although one still has an impression that there are letters there. It's as though they were in an unfamiliar alphabet. We substituted with English (i.e., Latin) letters on the left and Russian (i.e., Cyrillic) on the right, sparing the middle where the isolation fields are small enough to succeed. The letter substitution were chosen to be undetectable when crowded. This is the classic method of "silent substitution" (see Pelli & Tillman, 2007). Try it. While fixating the +, can you detect any difference between the upper and lower lines?

## Inhomogeneity of crowding within a word

Studies of RSVP reading at a specified vertical eccentricity have tended to assume that the whole word is at one radial eccentricity and thus has one critical spacing. However, in a horizontal line of text, letters that are farther from the vertical midline have greater radial eccentricity. Thus, the local critical spacing becomes larger and eventually exceeds the letter spacing (Appendix A).

More generally, in thinking about crowding and reading, there is an attractively simple but wrong idea that beguiled us for a year. Others too seem to have felt its pull, so let us dispel its allure. It once seemed to us that crowding might account for the cliff, but not the plateau, of the classic reading rate curve (Fig. 1). We thought crowding caused the steep drop when letters are too close (closer than critical spacing) and had no effect when the letters are farther apart than critical spacing. We thought the plateau represented a release from crowding. However, we were mistakenly assuming homogeneity of crowding, i.e., that there is one critical letter spacing for a whole word. Typically the word being read spans a range of eccentricities and the critical spacing varies proportionally, so only the more peripheral letters are crowded. (We are ignoring word breaks here, so put aside, for the moment, the separate fact that the word's end letters are less crowded because they are more exposed, Bouma, 1973.) What matters is the number of uncrowded letters. Reading is confined to this uncrowded span (Fig. 5). There is no escape. We will show that this span limits reading throughout the whole reading rate curve, including the plateau.

## Legge's conjecture: The visual span

It has been known for a century that reading proceeds at four fixations per second (Huey, 1908). This rate is preserved across the wide range of reading rates encountered in low vision and peripheral reading (Legge, 2007; Legge et al., 2001). This makes it natural to express reading rate as the product of fixation rate and the number of characters acquired in each fixation.

Woodworth (1938) asks, "How much can be read in a single fixation? Hold the eyes fixed on the first letter in a line of print and discover how far into the line you can see the words distinctly, and what impression you get of words still farther to the right. You can perhaps see one long word or three short ones distinctly and beyond that you get some impression of the length of the next word or two, with perhaps a letter or two standing out."

Legge et al. (2001) update this old idea to apply to RSVP, which minimizes movement of the eyes during reading. They propose that RSVP reading rate is limited by the *visual span*, the number of characters in a line of text that can be read without moving one's eyes. Here, we consider a stronger version of this conjecture, which we also attribute to Legge, namely, that RSVP reading rate is

**ine ehcsa tbe seocrd cpficr. "I beh rc  
s qenscrel-ebs husircss miqbf ba." Sbc  
bar hcsk tcr tbe letter from Xiroarf D'Am  
if fc Hemilton. His eyebrows warf uq es h  
Ha's eomirq bcne at three c'olcok." Ncne  
cen sac, ba qcints out tbet fhana's a de  
cd tnicrb cf mirc, Frir Kcllay, arswcre**

Crowded periphery	Uncrowded center	Crowded periphery
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Figure 5. The uncrowded window. This figure simulates crowding in reading by substituting letters in the peripheral field. Crowding spoils letter recognition, making reading impossible outside the uncrowded central field. As you read this caption, the words are clear and legible near your chosen point of fixation and illegibly crowded beyond that clear region. That central uncrowded field is a window through which you read. (The circular boundary shown here is a simplification. See Appendix B.) The idea of an uncrowded window limiting reading or search has been proposed under the names "span of apprehension" (Woodworth, 1938), "functional visual field" (Bouma, 1970, 1978), "conspicuity area" (Motter & Belky, 1998), and "number of elements processed per fixation" (Vlaskamp, Over, & Hooge, 2005).

proportional to visual span. We return to this in the Discussion section. Legge et al. define the visual span operationally: They measure letter recognition for triplets (random strings of three letters) as a function of position in the visual field. This is a slight variation on Bouma's (1970) classic crowding paradigm (Fig. 3). (Bouma assessed accuracy of reporting the middle letter of the triplet; Legge et al. assess average accuracy across all three letters.) Visual span is typically about 10 characters, extending slightly further to the right than to the left (Legge et al., 2001). That rightward bias for English, which is read from left to right, is reversed in Hebrew, which is read from right to left (Pollatsek, Bolozky, Well, & Rayner, 1981).

Legge (2007) augments this triplet-based operational definition of "visual span" by the suggestion that it measures the number of characters in a line of text that can be read without moving one's eyes. This latter idea, expressed by Woodworth above, has a long history in attempts to account for reading rate (Huey, 1908; Woodworth, 1938; Bouma, 1970, 1978; McConkie & Rayner, 1975; O'Regan, 1990, 1991; Engbert, Nuthmann, Richter, Kliegl, 2005; Vlaskamp, Over, & Hooge, 2005; Bosse & Valdois, 2007; see Legge, 2007, for review).

In sorting out the bewildering variety of "spans" that have been measured over the past century, we endorse O'Regan's (1990) suggestion of reserving "visual span" for measurements made with random letters and "perceptual span" for

measurements made with words. As O'Regan puts it, “‘visual span’ refers to what can be seen without the help of linguistic knowledge or context, whereas perceptual span includes what can be seen with that help.”

## Ordinary reading

Legge's conjecture is for RSVP, but what about ordinary reading of static text?

The McConkie & Rayner “moving window” technique is an elegant way to study ordinary reading. At each fixation by the observer, as she reads, some of the text is shown in its original form, and the rest of the text is replaced by a grating or X's. Text is replaced outside a “window” region defined relative to the observer's fixation. Effects of replacement on the observer's duration of fixation and saccade length indicate visual sensitivity to the substitution (McConkie & Rayner, 1975, 1976; Rayner, Inhoff, Morrison, Slowiaczek, & Bertera, 1981; Rayner, Well, & Pollatsek, 1980; Rayner, Well, Pollatsek, & Bertera, 1982).

Legge (2007) takes pains to distinguish his “visual span” from the “perceptual span” of McConkie and Rayner, which is defined as the range of characters (relative to the current fixation) that affect the eye movements of reading (McConkie & Rayner, 1975; Rayner, 1998). The eye-movement-based perceptual span is much more asymmetric, extending 15 characters to the right of fixation (three times as far as the visual span) and only 4 characters to the left (about the same as the visual span).

In his review, Rayner (1998) notes that, “The *word identification span* (or area from which words can be identified on a given fixation) is smaller than the total perceptual span (McConkie & Zola, 1987; Rayner et al., 1982; Underwood & McConkie, 1985) and generally does not exceed 7–8 letter spaces to the right of fixation.” Similarly, “When the first 3 letters of the word to the right of fixation were available and the remainder of the letters were replaced by visually similar letters, reading rate was not too different from when the entire word to the right was available” (Rayner, 1998, p. 381).<sup>1</sup>

Thus, in relating RSVP to ordinary reading, the similar widths suggest that Legge's visual span corresponds to this

<sup>1</sup>In principle, the much larger rightward extent of the eye-movement-based perceptual span could represent effects on eye movements of distant text features, such as word breaks or word shape, that are insufficient for letter and word identification. However, the evidence suggests that such effects do not extend far. The most common location of the first fixation in a word is the third letter in the word, independent of word length (McConkie, Kerr, Reddix, & Zola, 1988). Alternatively, the large perceptual span might be an artifact of the perceptually obvious substitutions used to measure it. Commenting on Rayner's studies, Underwood and McConkie (1985) note that finding an effect (on eye movements) of substitution by a square-wave grating or X's may reflect “interference” by these “perceptually obvious” insertions, “disruptive to normal reading for reasons other than the removal of normal textual information.”

“word identification span.” We return to this later, when we use a technique very similar to that of Underwood and McConkie (1985).

## The visual span is the uncrowded span

What limits the visual span? Acuity, crowding, lateral masking, and mislocalization are all named suspects. Legge et al. (2001) say that “visual span ... is jointly determined by decreasing letter acuity in peripheral vision, and lateral masking (crowding) between adjacent letters.”<sup>2</sup> However, the results presented in Figure 6 allow us to rule out all alternatives to crowding.

Bouma (1978) noted that “visual isolation” (“absence of interference from other stimuli”) “requires a surrounding homogeneous background with a radius almost half the ... target eccentricity.” We used Bouma's (1970) classic method to map out an observer's isolation fields at five locations in the visual field, measuring the required spacing for 80% correct identification of a central letter target when two flanker letters were displaced symmetrically at various angles relative to the target letter (Fig. 6). The measured critical spacing in all directions traces out an ellipse. The ellipses grow in proportion to eccentricity and point toward the fovea, as in Toet and Levi's (1992) study with upside-down and right-side-up T's. (This approach omits the in-out asymmetry, as explained in Footnote 9.) Furthermore, the ellipses are independent of letter size, as in Strasburger, Harvey, and Rentschler's (1991) study with numerical digits.

Acuity is threshold size. The nearly identical red (small letter), green (medium letter), and black (large letter)

<sup>2</sup>To this, Legge (personal communication) adds that mislocation errors (reporting the right letter in the wrong place in the triplet) “certainly play some role.” In his new book, Legge (2007, Section 3.7) calls this “decreasing accuracy of position signals in peripheral vision.” Legge et al. (2001) required observers to report all three letters in the triplet in the correct order. Strasburger (2005) too also reports that observers often mislocate numerical digits under conditions that produce crowding. Mislocating, i.e., reporting characters in the wrong order, could happen in at least two ways. We can imagine a cognitive account in which the observer mixes up the letter order in forming the report. However, a crowding account seems equally plausible. Crowding is the inappropriate integration of features into an object in which they do not belong. This can produce “feature migration” and illusory conjunction and would be expected to occasionally change the identity of a letter to that of a neighbor (Pelli et al., 2004). The cognitive and crowding accounts can be distinguished by comparing results in the left and right visual field. We would expect the cognitive effect to depend on the letter sequence, read left to right. We would expect the crowding effect to depend on radial eccentricity (distance from fixation). Legge et al. report that, on both sides of the vertical midline, the outermost letter of the triplet is identified much more accurately than the inner two, which are closer to the midline. These opposite order effects in left and right visual field are consistent with the crowding account and utterly unexpected in a cognitive account. Thus, any mislocation seems attributable to crowding, not a cognitive limitation.

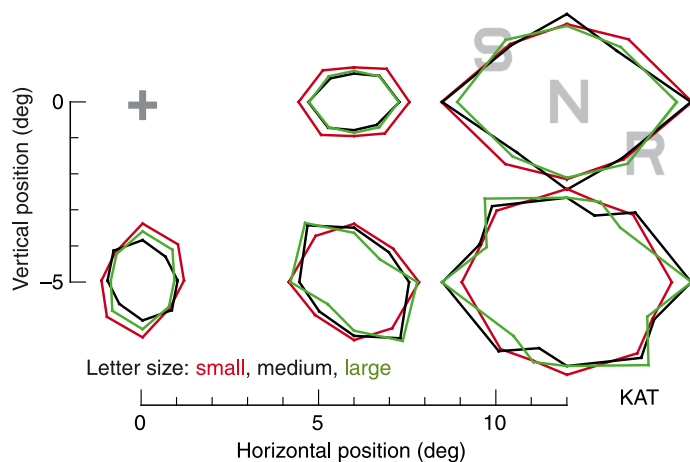


Figure 6. Isolation fields. The axes indicate position in the visual field, relative to the fixation point (grey “+” in upper left). In the upper right, also gray, we show a triplet: a target letter between two symmetrically arranged flankers. The colored contour lines trace out the center-to-center target-to-flanker spacing the observer required to achieve 80% correct identification of the target letter. At each eccentricity, the black, red, and green curves represent different letter sizes (see [Methods](#), [Table 1](#)). The results show that the critical spacing is proportional to radial eccentricity and independent of letter size. The symmetry of the plots results from the symmetry of the stimulus, which always had symmetrically opposed flankers. Each measured critical spacing is plotted as two opposing points. These contours were measured center to center. The full span of the isolation field, within which features are integrated, from outer edge to outer edge, extends half a letter further in every direction. Observer KAT.

curves in [Figure 6](#) show that there is hardly any effect of size on critical spacing. This proves that the critical spacing is not limited by acuity. In general, *lateral masking* is the effect of a nonoverlapping irrelevant pattern and includes a variety of phenomena and many models, but none, except crowding and surround suppression, are strongly dependent on eccentricity. Thus, the strong eccentricity dependence rules out all known forms of lateral masking except crowding and surround suppression. Surround suppression is similar to crowding in many ways, but we can rule it out because it only occurs when the flankers have higher contrast than the target (Chubb, Sperling, & Solomon, 1989; Petrov & McKee, 2006; Snowden & Hammett, 1998; Xing & Heeger, 2001; Zenger-Landolt & Koch, 2001), whereas here the target and flankers have equal contrast. We show that performance on the classic flanked letter task and the Legge et al. (2001) variation is determined solely by the ratio of actual to critical spacing (predicted by Bouma’s law), independent of size, spacing, and eccentricity per se. Theories other than crowding say those variables matter, but in fact they do not matter ([Fig. 6](#)), so we reject those theories. Only spacing matters (relative to the critical value, which depends only on location and direction in the visual field). Thus, identification of flanked letters is limited by crowding.

Legge et al. (2001) define the visual span profile as the performance on the flanked letter task, which is practically the same as Bouma’s classic crowding task. For any given spacing, critical spacing determines the farthest legible position from fixation. Thus, the visual span is the *uncrowded span*, the number of uncrowded character positions in a line of text ([Figs. 5](#) and [7](#)).

## Bouma’s law of crowding

Bouma (1970) observed that critical spacing is proportional to eccentricity. Toet and Levi (1992) confirmed this at the moderate and large eccentricities that Bouma tested, but found that a small additive offset (insignificant at large eccentricities) is needed to describe critical spacing at small eccentricities. This makes critical spacing a linear function of eccentricity,

$$s = s_0 + b\phi, \quad (1)$$

where  $\phi$  is the eccentricity (following Bouma),  $s_0$  is the critical spacing at zero eccentricity (about  $0.1^\circ$  or  $0.2^\circ$ ), and  $b$  is a proportionality constant that we name after Bouma. Characters spaced more widely than  $s$  are uncrowded.

(Of course, the transition from full to no crowding is gradual, so  $b$ , in fact, depends somewhat on the proportion correct that we take as “critical,” 80%. However, assuming an abrupt transition greatly simplifies the initial development of the model. As explained in [Appendix C](#), we add dither to the simple model to obtain graded psychometric functions that match those of human observers.)

A minor complication is that isolation fields are elliptical, not circular. [Appendix A](#) works out the geometry to estimate horizontal critical spacing at any place in the visual field ([Eq. A5](#)). (Our treatment omits the known in-out asymmetry of crowding, as explained in [Footnote 9](#).)

[Equation 1](#) (or [Eq. A5](#)) with a fixed  $b$  provides a good fit to data from some observers, but, as you will see below, to fit all the observers, from our laboratory and others, it is

+

xuncrowdedx

Figure 7. What is your uncrowded span at this vertical eccentricity? It is 3 if you can read “row” while fixating the plus sign, 4 for “crow,” 5 for “crowd,” and a whopping 9 for “uncrowded.” O’Regan (1990) calls this a “perceptual” span when measured with words, as here, and a “visual” span when measured with random letters.

necessary to allow  $b$  to have a linear dependence on eccentricity,

$$b = b_1 + b_2\varphi, \quad (2)$$

where  $b_1$  and  $b_2$  are observer-specific constants, independent of eccentricity  $\varphi$ . The effect of Equation 2 on Equation 1 is a further generalization of Bouma's law, from linear to quadratic, to accommodate individual differences. (Happily, this extension for differences among normals also allows the model to fit amblyopes as well, Levi et al., 2007.) This generalization bends Bouma's line but does not impact his fundamental observation that critical spacing is determined by eccentricity: It is the site, not the signal, that matters.

## Size or spacing?

The idea that letter size limits reading is ancient. Plato said it: "lacking keen eyesight, we were told to read small letters from a distance." The classic reading rate curves are all plotted as a function of letter size. Referring to the cliff in Figure 1, Legge, Pelli, Rubin, and Schleske (1985) assert that "the fairly rapid decline in reading rate for characters smaller than  $0.3^\circ$  is undoubtedly associated with acuity limitations." To the contrary, here, we prove that crowding, not acuity (i.e., spacing, not size), determines the position of the cliff.

Figure 6 demonstrates that the critical spacing of crowding is determined solely by position in the visual field. Performance of the flanked letter identification task depends on spacing, not size.

In ordinary text, letter size and letter spacing covary (as one changes viewing distance). One can plot reading rate as a function of either size or spacing. Breaking from tradition, we plot reading rate as a function of spacing, instead of size. Why change now? An acuity story is about size, but a crowding story is about spacing. Levi et al. (2007, their Fig. 2) show that doubling the normal letter spacing in the text shifts the reading rate curve, plotted as a function of size, by a factor of two. This shows that spacing matters, even when size is known. When, instead, they plot rate as a function of spacing, the curves for the two conditions coincide. This shows that size is irrelevant, once spacing is known. The traditional plot is based on size, which is irrelevant. It is better to plot as a function of spacing. Reading rate depends on spacing, not size.

When we say that size does not matter for reading of *ordinary text*, we suppose reasonable (center to center) spacing, enough to prevent overlap of neighboring letters, which is known to slow reading down (Chung, 2002), and no more than twice normal (for the font), since arbitrarily large spacing would reduce reading to identification of isolated letters. For well-corrected fluent readers with adequate light, when one shrinks ordinary text (e.g. by increasing viewing distance), it becomes unreadable, due

to crowding, before the acuity limit (for isolated letters) is reached.

For *ordinary conditions* (well-corrected fluent observers reading ordinary text at moderate luminance), we will see that the visual span is the uncrowded span over a wide range of text size (400:1 in Fig. 1; 5:1 in Levi et al. 2007). That is a large territory in which only spacing matters, but it has limits. With fixed letter spacing, reading eventually fails if contrast, (letter) size, or luminance is greatly reduced. (Reading slows at sunset, as afternoon fades into night.) We are inclined to attribute these failures to something other than crowding, because we suspect that the uncrowded span is independent of size, contrast, and luminance. Reading is impossible when text contrast falls below threshold for an isolated letter. Threshold contrast rises as size and luminance are reduced, so reducing contrast, letter size, or luminance reduces the ratio of text contrast to threshold contrast. Legge et al. (2007) show that reading rate is practically independent of contrast, provided contrast is at least four times threshold (0.04). Below 0.04, both visual span and reading rate gradually drop, reaching zero at threshold contrast (0.01). To believe that the reduced visual span found at near-threshold contrast is still the uncrowded span, we would need evidence that crowding is worse (critical spacing is greater) at low contrast. In fact, Pelli et al. (2004) found that critical spacing is independent of contrast over the range 0.1 to 1, and found no crowding at all at the contrasts they tested below 0.1. Thus, the visual span at contrasts less than four times threshold is limited by contrast, not spacing (crowding). It seems that the effects of reducing contrast, size, or luminance might all be described by one rule: The visual span is equal to the uncrowded span if text contrast is at least a factor of four above threshold for an isolated letter, and gradually shrinks to zero as text contrast approaches threshold.

## Eccentricity: Bouma versus Legge

Equating the uncrowded and visual spans links Bouma and Legge. This reveals an incompatibility in their assertions about eccentricity that was not apparent when they adopted their positions.

Legge et al. (2001) propose that the slower reading rate at greater eccentricity is due to shrinkage of the visual span: spanning fewer characters at greater eccentricity. Bouma showed that the critical spacing of crowding scales proportionally with eccentricity: Crowding is scale-invariant. Visual span is limited solely by crowding, so it must be scale-invariant too: spanning a fixed number of characters, independent of eccentricity. But wait, is scale invariance right or wrong?

Bouma claimed that  $b$  is constant, independent of eccentricity. Appendix B shows that the uncrowded span  $u$  is  $1 + 2/b$ , which is constant if  $b$  is constant. Legge et al.

(2001) find that visual span (in characters) falls with eccentricity and suggest that this accounts for the falling reading rate. Bouma's and Legge's claims are incompatible. In terms of Equation 2, Bouma would have said that  $b_2$  is zero, whereas Legge et al. would have said that  $b_2$  is large and positive. Surely they cannot both be right. It is an empirical issue.

If we scale the stimulus—size, spacing, and eccentricity (e.g., by reducing the viewing distance)—Bouma says the number of characters in the uncrowded span will be unchanged, whereas Legge says it shrinks. Only Bouma's position, not Legge's, is consistent with the general finding that resolution of many kinds is proportional to eccentricity at large eccentricity, i.e., scale-invariant (e.g., Herse & Bedell, 1989; Levi, Klein, & Aitsebaomo, 1985). This favors Bouma over Legge but is not decisive.

After many false starts, having tried to settle this in favor of Bouma or Legge, we finally conclude that neither position is exactly right. The true state of affairs seems to lie somewhere in between. Unsuspected by all (especially us) there is a great diversity among observers in how  $b$  depends on eccentricity (Fig. 9). We find that some individuals conform to Bouma's prediction and others to Legge's, but that most lie in between, conforming to neither prediction. In Figure 9, observers EK (green) and STC (red) have the zero and steep slopes claimed by Bouma and Legge, respectively, but most observers are intermediate between these extremes.  $b$  does grow with eccentricity ( $b_2 > 0$ ), demanding a generalization of Bouma's law (Eq. 2), but the growth is typically too small to account for much of the large drop in reading rate with eccentricity. RSVP reading rate drops with eccentricity, reaching one sixth the foveal rate at an eccentricity of  $20^\circ$  (Legge et al., 2001). Excluding STC and EK as outliers, for the other four observers in Figure 9,  $b$  roughly doubles as eccentricity increases from 0 to  $20^\circ$ , which roughly halves the uncrowded span  $u = 1 + 2/b$ . That goes in the right direction, but falls far short of accounting for the sixfold drop in reading rate.

Figures 8 and 9 depend on each other, and it is important to understand how they were made. First, for each condition and for each observer, we plotted proportion correct as a function of spacing, as in Figure 8, except that the horizontal scale was just spacing, not normalized. We call this a psychometric function. For each psychometric function we estimated the critical spacing  $s$  (threshold spacing for 80% correct). We then calculated Bouma's factor (roughly  $b \approx s/\phi$ , see Methods). In Figure 9, we plot  $b$  at the radial eccentricity  $\phi$  for that condition. We did a linear regression (Eq. 2) for each observer in Figure 9 to describe how his or her  $b$  depends on eccentricity  $\phi$ . This fit has two degrees of freedom: intercept  $b_1$  and slope  $b_2$ . For each observer, we used the fitted Equation 2 to model critical spacing for each condition (i.e., for each psychometric function). Finally, in Figure 8 we plot the proportion correct as a function of the ratio of the actual spacing to the model's critical spacing.

Thanks to all these steps, Figure 8 allows evaluation of the crowding hypothesis (i.e., performance depends solely on the ratio of actual to critical spacing) by inspection of essentially raw data. Each psychometric function in Figure 8 is a set of raw measurements shifted horizontally. The vertical scale is proportion correct, as measured, and the horizontal scale is spacing, normalized (i.e., shifted) by the model's critical spacing. The model (Eq. 2) allows each observer's  $b$  to have a linear dependence on eccentricity. The only contribution of the model to Figure 8 is to provide the model's critical spacing, which slides the psychometric function right or left.

Figure 8 presents results from six observers, three from Legge et al. (2001) and three of our own. In every case all the proportions correct very nearly trace out one curve as a function of spacing relative to critical spacing. (Even in the worst case, observer TAH in the lower right, the curves differ by less than 20%.) This shows that, within this wide range of conditions (size, spacing, and eccentricity), performance depends solely on the ratio of actual to critical spacing. Thus, these data (including the Legge et al. visual span functions) are fully accounted for by Bouma's (generalized) law of crowding. As a further test of Bouma's law, which makes no reference to size, our observers were tested with at least two letter sizes at each eccentricity (see Fig. 8 legends). The law prevails: The results show no effect of size.

With hindsight, it may now seem obvious that the visual span is the uncrowded span. Indeed, well before Legge and Bouma, even before crowding was called "crowding," Woodworth (1938) prefaced his description of perceptual span (above) with a description of crowding: "It seems strange that a word should need to be brought closer [to the fixation point] than a single letter. If the single letters can be read, why not the word composed of these letters? The answer is a mutual interference or masking of the letters in indirect vision." Bouma (1970) made the measurements and showed that crowding reduces the "functional visual field by a factor of four [which] exceeds by far any acuity expectations." However, this was not enough to convince the scientific community that reading is crowding-limited. Most subsequent authors cite Woodworth but nevertheless suppose that the span and rate are acuity limited. We already quoted our own confident assertion that the cliff of the reading rate curve is acuity limited (Legge, Pelli, Rubin, and Schleske, 1985). O'Regan (1990) cites Woodworth, but in the following year he introduces visual span as the "zone ... within which acuity limitations allow stimuli to be recognized" (O'Regan, 1991). Describing their SWIFT model, Engbert et al. (2005) note that reading speed is "related" to span and say, "We assume that processing speed is mainly limited by visual acuity, which is a function of the distance from ... the fovea." For their E-Z Reader model, Reichle, Rayner, and Pollatsek (2006) "adopted the assumption that the time needed ... is modulated by visual acuity ... It thus takes more time to identify long words and words that are farther from the

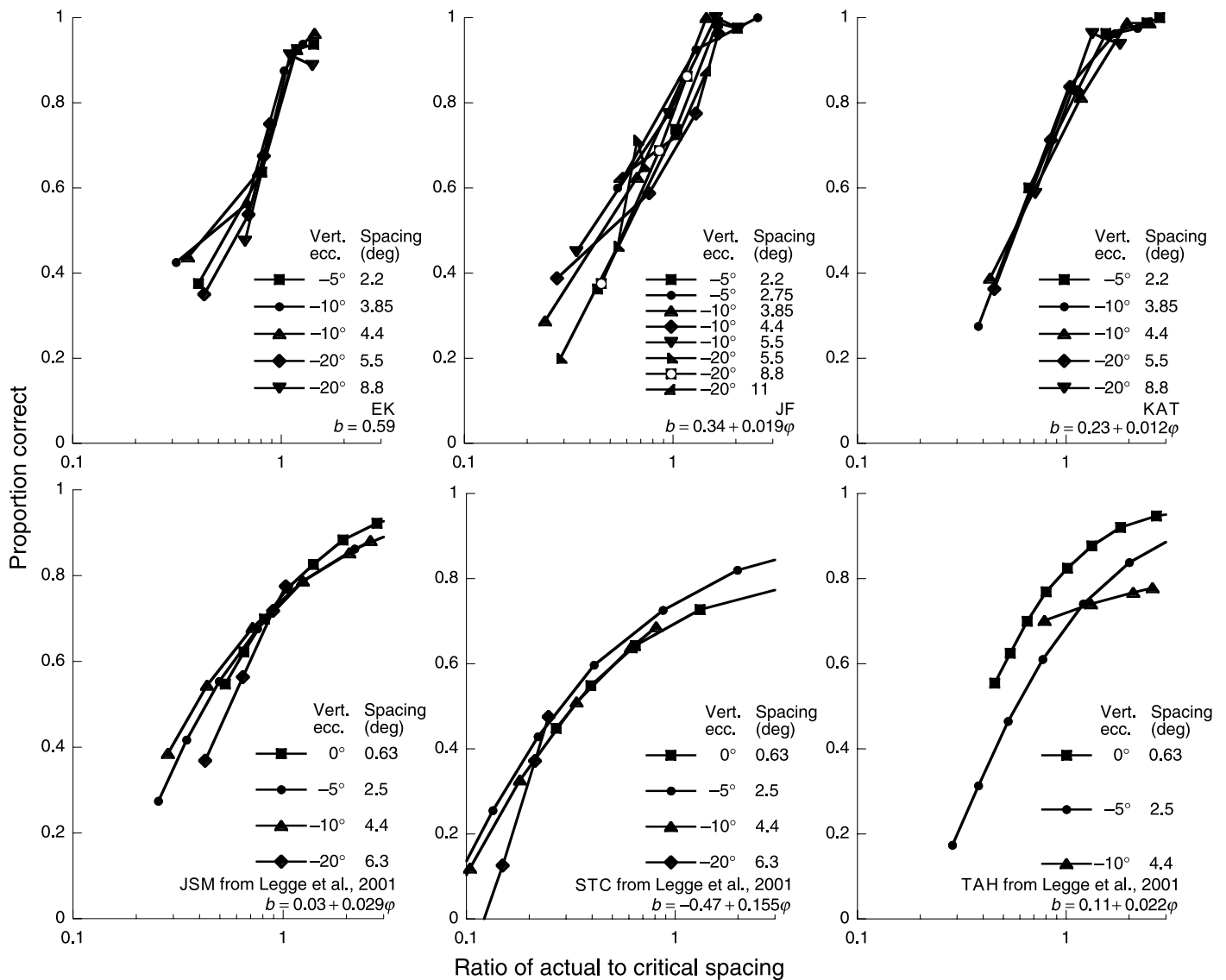


Figure 8. The classic measure of crowding: identification of a flanked letter (the middle letter in a triplet). Proportion correct is plotted as a function of letter spacing: the ratio of actual spacing to our model's critical spacing. Our model (a fit) is Bouma's law (Eq. A5), with only two degrees of freedom,  $b_1$  and  $b_2$  (Fig. 9), for all of each observer's data. The  $b$  formula (Eq. 2) with the fitted parameter values appears in the lower right of each graph. (The criterion for "critical" is 80% correct.) In each panel all the conditions (eccentricities, spacings, and sizes) very nearly collapse onto a single curve. This indicates that, within the range of conditions we explored, performance depends solely on relative spacing, i.e., it is fully accounted for by Bouma's generalized law of crowding. Vertical eccentricity is designated by symbol type. Points are for successive letter positions to the right of the vertical midline. The top three graphs are for our observers EK, JF, and KAT. The bottom three graphs are for observers JSM, STC, and TAH, replotted from Legge et al. (2001, Fig. 4, right visual field). They reported the average performance  $p_3$  for all three letters in a triplet, noting similar performance for the inner two letters and much better performance for the outermost letter. Supposing that the outer letter was always correctly identified, we estimated the middle letter performance as  $(3p_3 - 1) / 2$ . The Legge et al. curves are smooth because we digitized their Gaussian fits instead of their raw scores.

fovea." The idea of an uncrowded window limiting reading or search has been proposed under the names "span of apprehension" (Woodworth, 1938), "functional visual field" (Bouma, 1970, 1978), "conspicuity area" (Motter & Belky, 1998), and "number of elements processed per fixation" (Vlaskamp, Over, & Hooge, 2005).

From the beginning, we sought to replot the visual span data as crowding curves, as in Figure 8, to show that all

that matters is the ratio of actual to critical spacing. But our plots did not collapse into skinny curves until we cleared three conceptual hurdles. First, as noted above, we had to discard the false assumption that crowding would be homogeneous throughout a word. While a word typically has one vertical eccentricity, each letter has a different radial eccentricity, so, second, we had to work out the geometry of how this affects the critical spacing

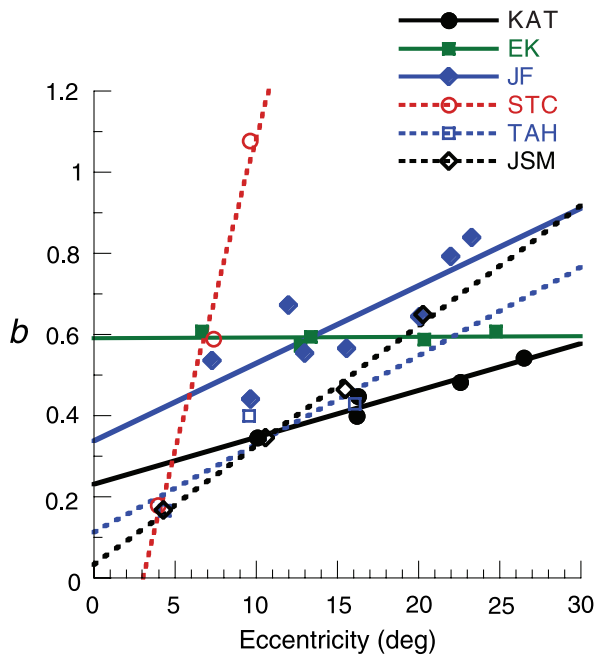


Figure 9. Bouma's critical spacing factor  $b$  as a function of eccentricity, one point for each psychometric function in Figure 8. A linear regression line (Eq. 2) has been fit to each observer's results. (The values of  $b_1$  and  $b_2$  appear in the equation in the lower right of each graph in Fig. 8.) Regarding Bouma versus Legge, the steep red line (open circles, observer STC) supports Legge, and the level green line (filled squares, observer EK) supports Bouma. The other four observers have modest nonzero slopes between these two extremes. (The two degrees of freedom in Eq. 2 correspond to each line's Y intercept  $b_1$  and slope  $b_2$ . Parameter  $b_2$  is solely responsible for the collapse seen in each panel of Fig. 8; parameter  $b_1$  merely shifts all the curves, as a group, left and right.) These individual differences seem to be stable, not a result of practice. At large eccentricity, STC has the worst crowding, yet Chung (2002) notes (personal communication) that STC was the most practiced at those eccentricities.

through the size and orientation of the relevant elliptical isolation field (Appendix A). Third, it took a lot of data to convince us that Bouma's "constant" varies with eccentricity (Fig. 9), violating the general scaling laws. It was only after plotting Figure 9 and understanding its implication that we were able to generalize Bouma's law (Eq. 2) and plot the clean Figure 8 that you see.

So far, we have established that the classic crowding measure, with a letter triplet, really does conform to a simple rule, Bouma's generalized law, yet reveals striking individual differences in how Bouma's "constant" depends on eccentricity. Now let us turn to reading.

### Bouma and Legge reconciled: The uncrowded span model of reading rate

We now combine Bouma's law and Legge's conjecture to predict reading rate.

As noted above, Legge et al. (2001) postulated that reading rate is limited by the "visual span," operationally defined in terms of flanked letter identification. They mapped the identifiability of a triplet consisting of three random letters over the relevant part of the visual field. This "visual span function" describes proportion correct as a function of letter position in the visual field for text of a given size, spacing, and vertical eccentricity. They noted the similarity of their triplet test to Bouma's crowding test but suggested that the triplet performance might be limited by acuity, crowding, masking, or mislocalization (Footnote 2). In fact, Figures 6 and 8 rule out all the alternatives, showing that the triplet performance they measured is limited solely by crowding. Thus, the operationally defined "visual span" measures the number of uncrowded character positions in a line of text at a given spacing and vertical eccentricity (centered on the vertical midline). We call this the uncrowded span  $u$  and write the conjecture as

$$r = \rho u, \quad (3)$$

where  $r$  is the reading rate (characters per second) and  $\rho$  is a proportionality constant with a value on the order of 10 Hz. (As a mnemonic, think of  $\rho$  as the rate of glimpses and  $u$  as the number of letters harvested per glimpse.) We define  $r$  as characters per second, but we measure and report the traditional word/min. For English text, with an average of five letters plus a space per word, 1 word/min equals 0.1 character per second. For casual reading of a static page, typical values might be 280 word/min (i.e.,  $r = 28$  character/s), a  $\rho$  of 4 Hz, and a span of 7. For central RSVP reading, participants striving to read as quickly as possible reach a rate of 910 word/min (i.e.,  $r = 91$  character/s) with a  $\rho$  of 13 Hz and a span of 7. (We return to this comparison in the Discussion section.) The uncrowded span  $u$  depends solely on the spacing, the critical spacing constant  $b$ , and the eccentricity. In writing

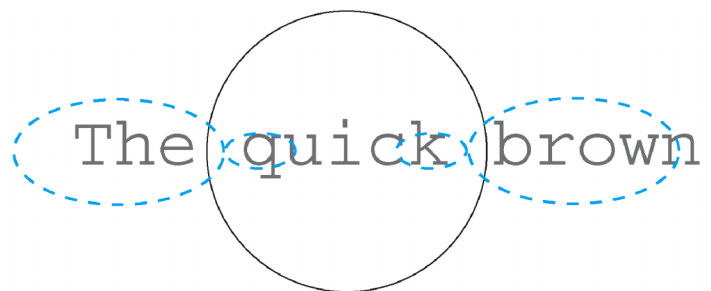


Figure 10. Critical spacing and the uncrowded window. The black circle is the uncrowded window (Fig. 5). The observer is fixating the letter "i." Critical spacing, represented by the blue ellipses, increases in proportion to eccentricity (Fig. 6), but the letter spacing is uniform (except for word breaks). Letters inside the circle are uncrowded, because their spacing is greater than critical. Letters outside the circle are crowded, because their spacing is less than critical.

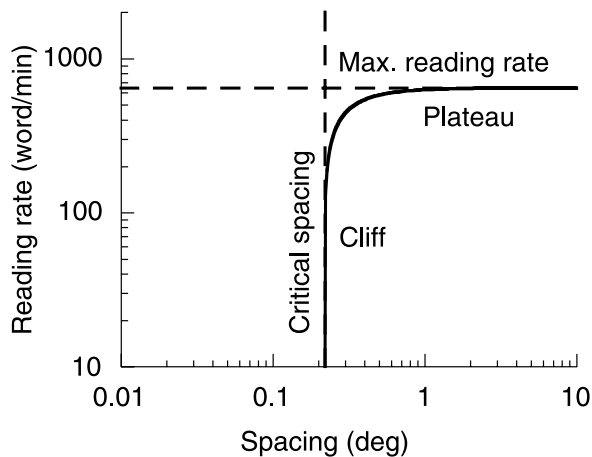


Figure 11. Cliff and plateau. Reading rate predicted by Equation 5. The reading rate curve has the classic shape: a steep rise to a flat plateau. The plateau is at the maximum reading rate  $r \approx 2\rho/b$ . The cliff edge is the critical spacing for reading  $s \approx b\varphi_v$ , beyond which reading rate is asymptotically independent of spacing. The critical spacing for reading is closely related to the “critical print size” of Chung et al. (1998). See Footnote 4.

Equation 3, one anticipates that the proportionality constant  $\rho$  will be independent of most experimental variables. Its variation among observers and with text difficulty was expected, but it is surprising that  $\rho$  falls with increasing eccentricity.

Consider a horizontal row of uniformly spaced characters at a vertical eccentricity  $\varphi_v$ . The letter spacing is fixed, but the observer’s critical spacing increases with the horizontal eccentricity (Fig. 6). This happens partly because the radial eccentricity increases (Eq. 1) and partly because the orientation of the elliptical isolation fields (always aligned with fixation) becomes less favorable (Appendix A). Figure 10 shows how Bouma’s law determines the uncrowded window. Starting from the midline and proceeding to greater horizontal eccentricity to the right or left, eventually the critical spacing, increasing with eccentricity, grows to exceed the given spacing of the text. This is the edge of the *uncrowded span*. Beyond that span, spacing will be less than critical and the letters will be crowded (Fig. 5). The proportion-correct criterion for “critical” is to some extent arbitrary. Bouma used 100%. We use 80%, which results in a smaller value of  $b$ . Appendices A and B work out the geometry to derive an expression for  $u$ , the width of the span (Eq. B10). We use that expression, which is exact, in the rest of our plots, but in Figure 11 we present a simple approximation that retains the important features of the exact expression:

$$u \approx \frac{2}{b} \sqrt{1 - \frac{b^2 \varphi_v^2}{s^2}}, \quad (4)$$

where  $b$  is Bouma’s constant,  $\varphi_v$  is the vertical eccentricity, and  $s$  is the center-to-center letter spacing. For simplicity, this approximation, based on Equation B7, assumes that the ellipse is a circle ( $\varepsilon = 1$ ), ignores the perspective transformation that compresses the angular spacing of eccentric letters, neglects the minimum critical spacing found at small eccentricity ( $s_0 = 0$ ), and omits the +1 conversion from breadth to span (Appendix B). Combining Equations 3 and 4, the predicted reading rate is approximately

$$r \approx \frac{2\rho}{b} \sqrt{1 - \frac{b^2 \varphi_v^2}{s^2}}. \quad (5)$$

This simple curve for reading rate (Fig. 11) is like the human data. It has a flat plateau  $2\rho/b$  at large spacing (where the square root term approaches 1) and drops abruptly to zero as spacing  $s$  is reduced to the critical spacing  $b\varphi_v$  at the vertical midline. Assuming only Bouma’s law, Appendix A calculates the cliff (Eq. A6) and Appendix B calculates the plateau (Eq. B8). In general, for arbitrary ellipticity  $\varepsilon$  and nonzero minimum critical spacing  $s_0$ , the curve is characterized by its horizontal and vertical asymptotes: maximum reading rate  $(1 + 2/b)\rho$  (Eqs. 3 and B8) and critical spacing for reading  $s_0 + b\varphi_v/\varepsilon$  (Eq. A6).

Let us now compare the model with human data. Chung, Mansfield, and Legge (1998) measured reading rate as a function of size and spacing at six vertical eccentricities. They fit their results by eye with a two-line model (not shown here), which fits well but has no theoretical basis and has three degrees of freedom for each curve. The uncrowded span model (Eqs. B10 and C1) fits even better, achieving the same RMS error with only two degrees of freedom,  $b$  and  $\rho$ , for each curve (Fig. 12).<sup>3,4</sup>

Legge et al. (2001) advertise the large unexpected effect of eccentricity on RSVP reading rate as a challenge to

<sup>3</sup>Chung et al. (1998) did their two-line fits by eye. We redid them by computer, minimizing RMS log error. With three degrees of freedom the two-line fit yields the same RMS error as the uncrowded span model, which has only two degrees of freedom. The average log-log slope of the cliff in the two-line fits was 3. Fixing that slope at 3 and fitting the two-line model with only two degrees of freedom yields an RMS error that was, on average,  $1.3 \pm 0.1$  times that of the fit by the uncrowded span model.

<sup>4</sup>In comparing studies, some readers may wish to convert critical spacing, as estimated here (Eq. A6), to critical print size, as estimated by Chung et al. (1998) and others from a two-line fit. For the 36 fits (6 observers  $\times$  6 eccentricities) in Figure 12, the mean  $\pm$  standard deviation of the ratio of critical print size to critical spacing is  $0.9 \pm 0.2$ . In converting other data, we suggest two steps. First, take the critical spacing as an estimate of what one might call “critical print spacing,” and then calculate the size from the spacing, based on the actual text’s metrics. For Chung’s Times Roman text, we estimate the letter size to be  $0.9 \times$  spacing. The fitting software we provide fits both models (uncrowded span and the two-line fit) to any reading-rate data.

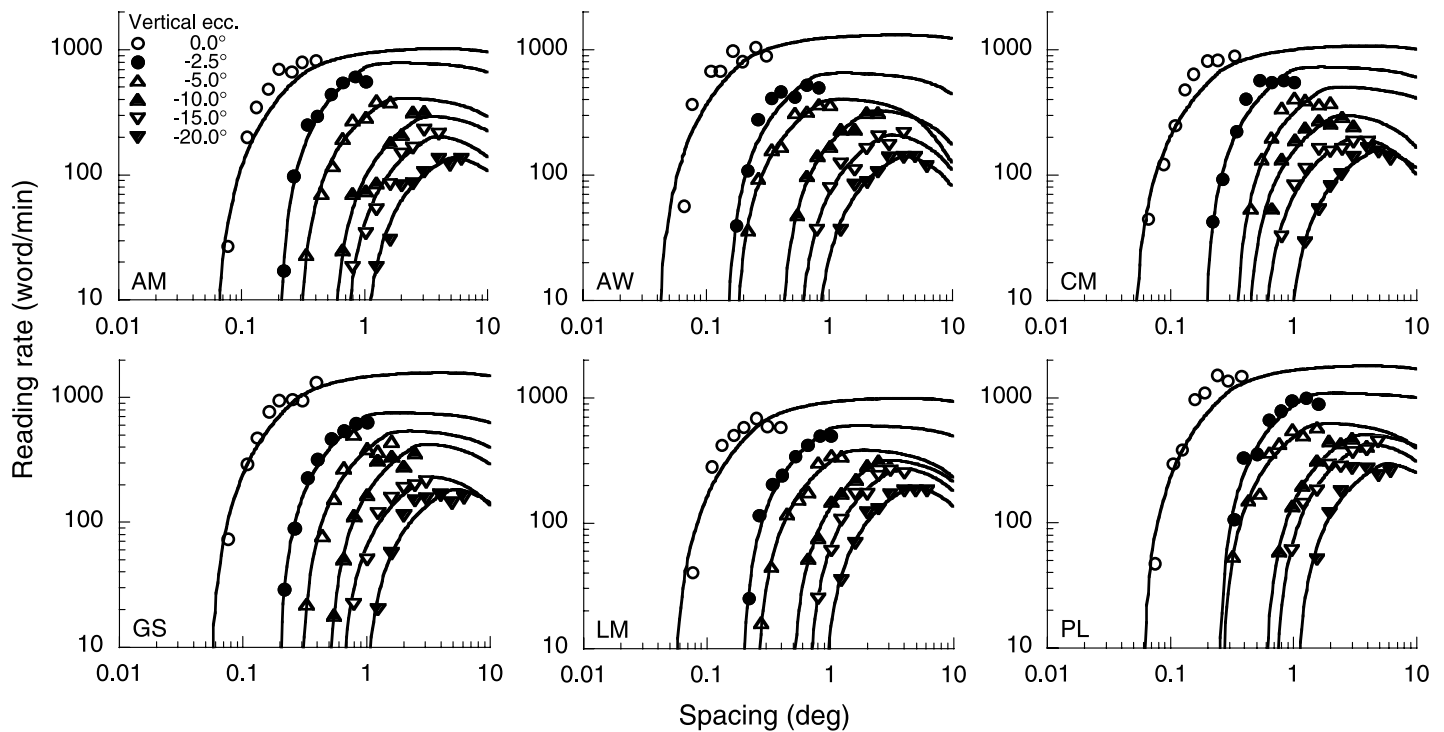


Figure 12. Reading rate. Our model (Eqs. B10 and C1) fits the Chung et al. (1998) data well (6 observers), with only two degrees of freedom,  $b$  and  $\rho$ , for each curve (vertical eccentricity). (We fix the ellipticity  $\varepsilon = 2$  and minimum critical spacing  $s_0 = 0.2^\circ$ . Vertical eccentricity  $0^\circ$  is a special case; we fix  $b = 0.5$  and take  $s_0$  as a degree of freedom.) The vertical eccentricities are  $0^\circ$ ,  $-2.5^\circ$ ,  $-5^\circ$ ,  $-10^\circ$ ,  $-15^\circ$ , and  $-20^\circ$ . For their Times Roman font, we estimate that letter spacing is  $1.1 \times$  size. The droop at very large spacing is a known feature of human curves (Fig. 1). In the uncrowded span model, it is a consequence of perspective compression at large eccentricities (Eq. B10). The MATLAB program that made these fits is available from <http://psych.nyu.edu/pelli/software.html>.

models of reading rate. Fitting our uncrowded span model to the Chung et al. (1998) data fixes the model's parameters and allows us to compare the eccentricity dependence of the observer's reading rate and uncrowded span (Fig. 13). Remember that the uncrowded span model supposes that reading rate  $r$  is the product of  $\rho$  and  $u$  (Eq. 2). The graphs in Figure 13 have consistent vertical scales (0.9 log unit per inch) and identical horizontal scales. Thus, the slopes of  $\log \rho$  (Fig. 13b) and  $\log u$  (Fig. 13c) must sum to the slope of  $\log r$  (Fig. 13a). As Legge et al. note, reading rate drops with eccentricity, approximately a straight line in these log-linear coordinates, falling sixfold from  $0^\circ$  to  $20^\circ$ . In effect, Legge et al. supposed that the proportionality constant  $\rho$  is fixed, independent of eccentricity, and that  $u$  shrinks with eccentricity. Their attempt to test this eccentricity conjecture was inconclusive because the bounds on their model's predicted performance were too broad. Contrary to what they supposed, Figure 13 shows that the span  $u$  of these six observers hardly changes with eccentricity. The uncrowded span model fits the measured rates by reducing  $\rho$ , not  $u$ .

In other words, given the drop in reading rate  $r$  with increasing eccentricity, Legge et al. (2001) predicted that  $u$  would drop and  $\rho$  would be flat, but we find instead that

$\rho$  drops and  $u$  is flat. This invalidates the Legge et al. claim that changes in  $u$  account for slow peripheral reading, but we are still at a loss to explain why  $\rho$  drops with increasing eccentricity.<sup>5</sup>

Establishing this unified account required that we resolve the discrepancy between the Bouma and Legge claims about the effect of eccentricity on span. To our surprise, both positions are shifted by this reconciliation. However, let us not lose perspective. This compromise does not disturb their central claims. Bouma's generalized law retains the essential insight that critical spacing depends

<sup>5</sup>As we mentioned briefly at the beginning, Legge et al. (2001, p. 726) list many possible determinants of visual span, including crowding, and note that some of those causes would predict a plateau: "A consequence of the linear scaling laws that apply to both peripheral letter acuity and crowding ... is that the size of the visual span is roughly constant when measured in letter spaces over a moderate range of angular character size." (O'Regan, 1990, made the same point.) However, we take the Legge et al. comment as a hypothetical aside, not their preferred account, because the linear scaling laws also make the visual span independent of vertical eccentricity, contradicting the central thesis of their paper, namely, that shrinkage of the visual span accounts for slower reading at greater eccentricity.

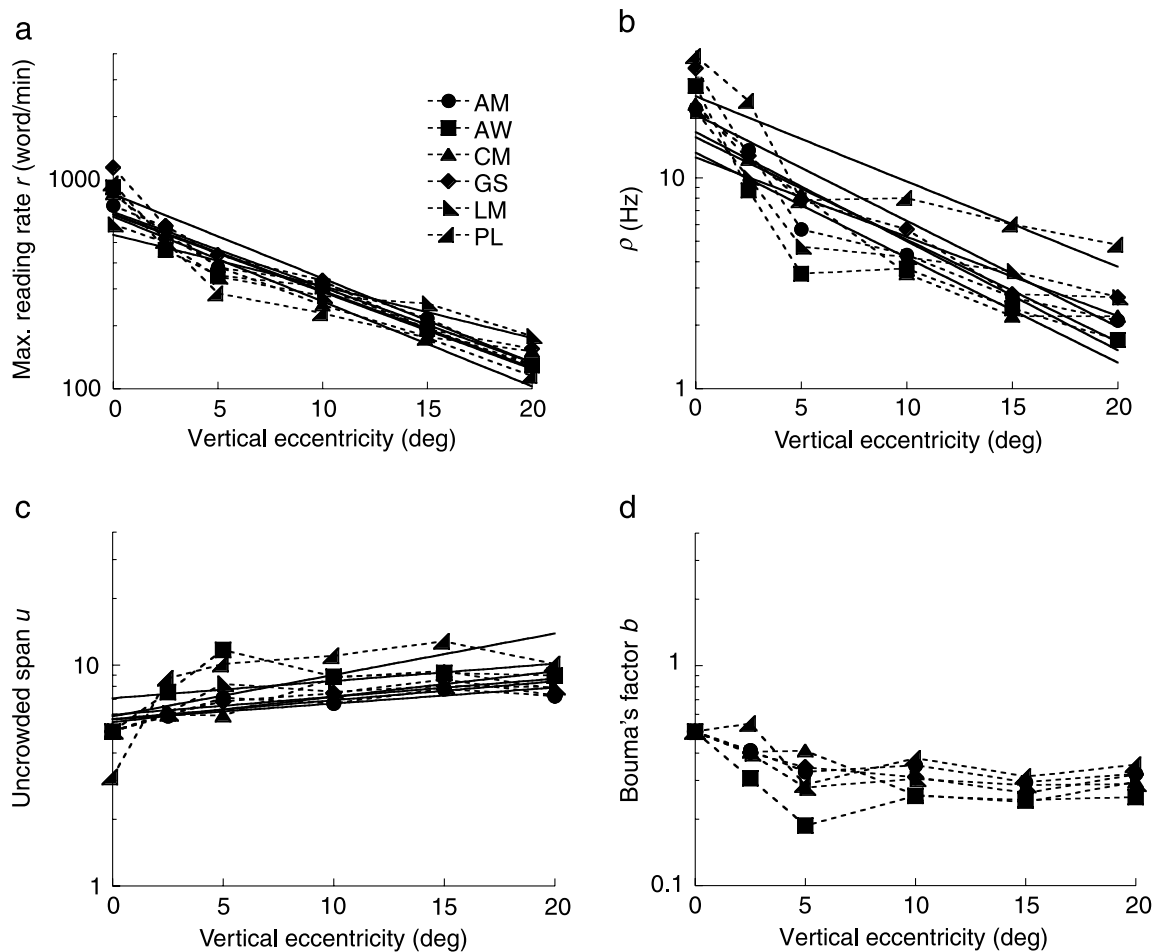


Figure 13. Effects of eccentricity. Based on the data in Figure 12. (a) The maximum reading rate estimated by Chung et al. (1998) from their two-line fit to the data at each vertical eccentricity (in lower visual field). This is a big effect; reading rate drops sixfold from  $0^\circ$  to  $20^\circ$ . While there is no known reason for any of these graphs to be straight, the linear regression lines do fit well enough for us to take their log-linear slope as a summary of the eccentricity dependence. The mean slope of the regression lines in (a) is  $-0.04$  decade/deg, with a standard deviation of  $0.006$ . Note that, in the model (Eq. 3), reading rate  $r$  (character per second) is the product  $\rho u$ , so  $\log r = \log \rho + \log u$  and  $\frac{d \log r}{d \phi} = \frac{d \log \rho}{d \phi} + \frac{d \log u}{d \phi}$ . Thus, the slopes of  $\log \rho$  (panel b) and  $\log u$  (panel c) must sum to the slope of  $\log r$  (panel a). (b) The rate factor  $\rho$  at each eccentricity. The mean slope is  $-0.05$  decade/deg. (c) The uncrowded span  $u = 1 + 2/b$  for large spacing (Eq. B8) at each eccentricity. The mean slope is  $+0.01$  decade/deg. The drop in  $r$  is accounted for by the drop in  $\rho$ ; there is no drop in  $u$  for these observers. English text has an average of 5 printed characters and a space for each word so  $1 \text{ word/min} = (5 + 1 \text{ character}) / (60 \text{ s}) = 0.1 \text{ character/s}$ . (d) Bouma's factor  $b$ . Note that there is much less variation in this Chung et al. group of observers than in the Legge et al. (2001) observers plotted in Figure 8.

solely on eccentricity: It is the site, not the signal, that matters. Legge's demonstrations that reading speed is strongly correlated with the visual span still suggest that the visual span is an important determinant of reading speed. In the next section, we will show how the visual span, which is the uncrowded span, limits reading rate.

## Proof

We have seen that the uncrowded span model (reading rate is proportional to uncrowded span, Eq. 3) provides a

plausible account of reading rate's dependence on spacing (Fig. 12). As spacing increases beyond its critical value, reading rate rises steeply and then remains at maximum rate, out to large spacings. The graph has two parts: the cliff and the plateau (Fig. 11). The cliff, a nearly vertical line, is characterized by its horizontal position: the critical spacing. The plateau, a horizontal line, is characterized by its vertical position: the maximum reading rate.

So far we have merely established the plausibility of the crowding account of reading rate. To prove it, we now show that crowding determines the positions of the cliff and plateau for reading. Appendices A and B prove it for the model. Four experiments (three here, one in Levi et al., 2007) prove it for the observers.

## The cliff is crowded

The cliff is at the critical spacing for reading. Is that spacing the same as the critical spacing for crowding found with Bouma’s classic letter identification task? Fifty years ago, one might have supposed that the letter identification task used in the classic crowding test was unrelated to reading, with no assurance that letter identification and reading would have the same spacing requirements. However, there is now much evidence that reading is mediated by letter identification, so we expect the failure of letter identification at critical spacing to devastate reading (Pelli, Burns, Farell, & Moore-Page, 2006; Pelli, Farell, & Moore, 2003).

Levi et al. (2007) measure the critical spacing for identifying a letter and for reading. They test normal and amblyopic observers with words presented at  $0^\circ$  and  $-5^\circ$  vertical eccentricity. They find the two measures of critical spacing to be equal in every case:  $0^\circ$  and  $-5^\circ$  eccentricity, in normal, nonamblyopic, and amblyopic eyes. Equal critical spacing is strong evidence that the cliff in reading rate is due to crowding.

## The plateau is crowded

The height of the plateau is reading rate, which the model supposes to be proportional to uncrowded span. The uncrowded span is limited at both ends by the critical spacing (Fig. 5). So, the plateau is limited by critical spacing, i.e., “is crowded,” provided the supposed proportionality holds. Let us now replace supposition by proof.

Thus far, the link between crowding and maximum reading rate (the vertical position of the plateau) has been weak. We have Legge’s conjecture (Eq. 3) that reading rate is proportional to visual span, inspired by performance of the Mr. Chips model (Legge, Klitz, & Tjan, 1997b). Legge, Cheung, Yu, Chung, Lee, & Owens (2007) find a high correlation between log reading rate and visual span when they vary contrast, size, and eccentricity of the text, but that finding is much weaker than proving proportionality or causality: namely, that span *determines* reading rate rather than simply being an independent consequence of the manipulation of visibility. We return to this in the Discussion section. We have just seen that attempts to confirm proportionality, by looking for corresponding changes in visual span and maximum reading rate with eccentricity, have failed (Fig. 13). For some observers (e.g., STC), the link seems to hold, but for most observers only a small part of the drop in reading rate with eccentricity is accounted for by reduced visual span  $1 + 2/b$ . In terms of Equation 3, the drop in reading rate is accounted for mostly by reducing the rate parameter  $\rho$ , which has no theoretical basis.

The uncrowded span model has two degrees of freedom,  $b$  and  $\rho$ . Both affect reading rate, so it might seem that we could attribute changes in reading rate to either parameter.

However,  $b$  is the critical spacing constant and is thus determined by the position of the cliff, leaving only  $\rho$  to absorb any independent variation of reading rate.

Is the uncrowded span truly a restrictive window through which the observer must read? To answer this, we directly measure the span for reading—the range of character positions that contribute to reading—and compare it with the uncrowded span  $u = 1 + 2/b$ . We do this in three ways and at several eccentricities (Fig. 14). At each eccentricity, every method indicates that reading rate is proportional to the uncrowded span.

### Displace the word

The first method measures the RSVP reading rate for a stream of randomly selected four-letter words, as a function of the horizontal position  $h$  of the center of the word relative to fixation (Fig. 15). Reading rate is highest at zero offset and declines monotonically, reaching zero at an offset of five to eight letters, depending on the vertical eccentricity. The rectilinear curve through the data represents our model: Reading rate is proportional to the number of characters within the observer’s uncrowded span,

$$r = \rho \max\left(0, \min(u/2, h + 2) - \max(-u/2, h - 2)\right), \quad (6)$$

where the observer’s uncrowded span has bounds  $(-u/2, u/2)$  and the four-letter word centered at position  $h$  has bounds  $(h - 2, h + 2)$ . The best-fitting value of  $u$  is 8.1 at vertical eccentricity  $0^\circ$ , 7.4 at  $-5^\circ$ , and 5.3 at  $-20^\circ$ .

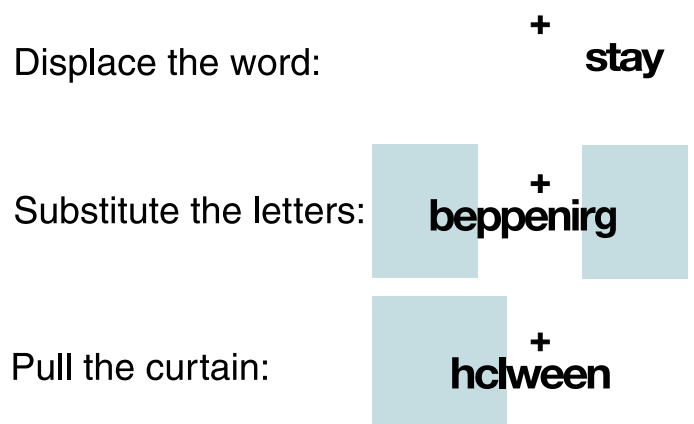


Figure 14. Three ways to measure the span for reading. *Displace the word.* Measure reading rate (RSVP) for random four-letter words as a function of position. *Substitute the letters.* Measure reading rate as a function of the unsubstituted span, within which letters are presented faithfully. (The substitution regions are tinted blue in this illustration, but they were not marked in any way in the actual experiments.) *Pull the curtain.* Measure reading rate as a function of the position of the left (or right) edge of the (large) unsubstituted span.

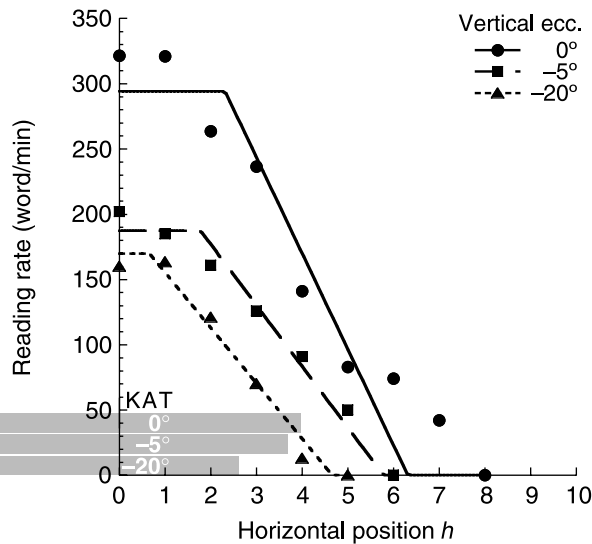


Figure 15. Displace the word. Reading rate as a function of the horizontal position (number of letters to the right of fixation) on which a four-letter word is centered. We measure threshold reading rates for unordered four-letter words. The line is the fit by Equation 6. The horizontal gray bars represent the uncrowded span  $u$  estimated by the model fit.  $u$  is 8.1 at vertical eccentricity  $0^\circ$ , 7.4 at  $-5^\circ$ , and 5.3 at  $-20^\circ$ . Observer KAT.

Our calculation of uncrowded span (Appendix B) assumes that the target letter is flanked by letters on both sides. Ordinary text, today,<sup>6</sup> has space between words, so the end letters are exposed, each flanked on only one side. These end letters are less crowded. We avoided this complication in the data we collected for Figures 15–19 by adding flankers,  $x$ , at the beginning and end of each word in the RSVP presentation. This makes it more reasonable to expect equality of the word- and letter-based estimates of the uncrowded span.

**Substitute the letters**

We have no idea why  $\rho$  depends on eccentricity. Even so, we can still ask, for any given eccentricity (and  $\rho$ ), does the uncrowded span determine the reading rate? We do not know any way to increase the uncrowded span, but we devised a way to effectively reduce it.

We used the classic technique of silent substitution to measure how reading rate depends on the effective uncrowded span. The trick is to simulate crowding by letter substitution. Some letter substitutions greatly impair legibility of text yet are undetectable when crowded, as illustrated in Figures 4 and 5 (Pelli & Tillman, 2007).

This is similar to the moving window of Underwood and McConkie (1985). Using an eye-position-contingent display, they created an unsubstituted window around the

<sup>6</sup>Noordzij (2005) suggests that word breaks first appeared in written documents sometime in the years 600–650 AD, initially in Ireland, and quickly spread to the rest of Europe.

current fixation. Text was displayed faithfully within the window and was substituted beyond the window. They substituted letters so as to destroy letter identity yet preserve word shape. They defined “word shape” as the gross outline, and selected substitute letters from the original letter’s category: having an ascender (e.g., bh), descender (e.g., pq), or neither (e.g., ac). However, although hallowed by tradition, there is no theoretical or empirical basis for that definition of word shape. We instead define word shape operationally (what can be distinguished when crowded) and choose the letter substitutes so as to be visually indistinguishable from the original when crowded. However, this is less different than it sounds, as our letter substitution table turns out to be similar to theirs.

We measured the RSVP reading rate with some letters substituted (Fig. 16). We suppose that the observer has an (unknown) uncrowded span  $u$  and that letters displayed outside that span are crowded. The experimenter defines an *unsubstituted* span  $U$ , on the display, within which letters are displayed normally. Letters outside that span are substituted. In modeling reading under these conditions, we suppose that substituting crowded letters has no effect on reading, because it is a “silent” substitution, invisible to the observer. Any measured effect must be due to substitution of uncrowded letters. With both spans centered at fixation, we suppose that reading is limited by whichever is narrower,

$$r = r_0 + \rho \min(u, U), \tag{7}$$

where  $r$  is the reading rate,  $r_0$  is the residual reading rate when all the letters are substituted (i.e.,  $U = 0$ ),  $\rho$  is the rate parameter,  $u$  is the observer’s uncrowded span, and  $U$  is the display’s unsubstituted span.

Figure 16 shows the stimulus. Figure 17 shows results for two observers at three eccentricities, plotting reading

$U=0$	$U=2$	$U=4$	$U=6$
	—	— —	— — —
<b>Lt</b>	<b>It</b>	<b>It</b>	<b>It</b>
<b>wes</b>	<b>was</b>	<b>was</b>	<b>was</b>
<b>beqqcrirg</b>	<b>beqpenirg</b>	<b>beppenirg</b>	<b>bappening</b>
<b>egeir.</b>	<b>egair.</b>	<b>again.</b>	<b>again.</b>
<b>Gbenlay</b>	<b>Gbarlay</b>	<b>Gharley</b>	<b>Charley</b>
<b>wculdr't</b>	<b>wculdr't</b>	<b>wouldn't</b>	<b>wouldn't</b>
<b>stey</b>	<b>stay</b>	<b>stay</b>	<b>stay</b>
<b>lockad</b>	<b>lckkad</b>	<b>locked</b>	<b>locked</b>
<b>ir</b>	<b>in</b>	<b>in</b>	<b>in</b>
<b>tba</b>	<b>the</b>	<b>the</b>	<b>the</b>
<b>scenct</b>	<b>sccrct</b>	<b>secret</b>	<b>secret</b>
<b>qleec.</b>	<b>qlaca.</b>	<b>place.</b>	<b>place.</b>

Figure 16. The unsubstituted span. The middle  $U$  letters are presented faithfully (unsubstituted). All letters beyond that unsubstituted span are subject to substitution, as specified by Table 3 in the Methods section.

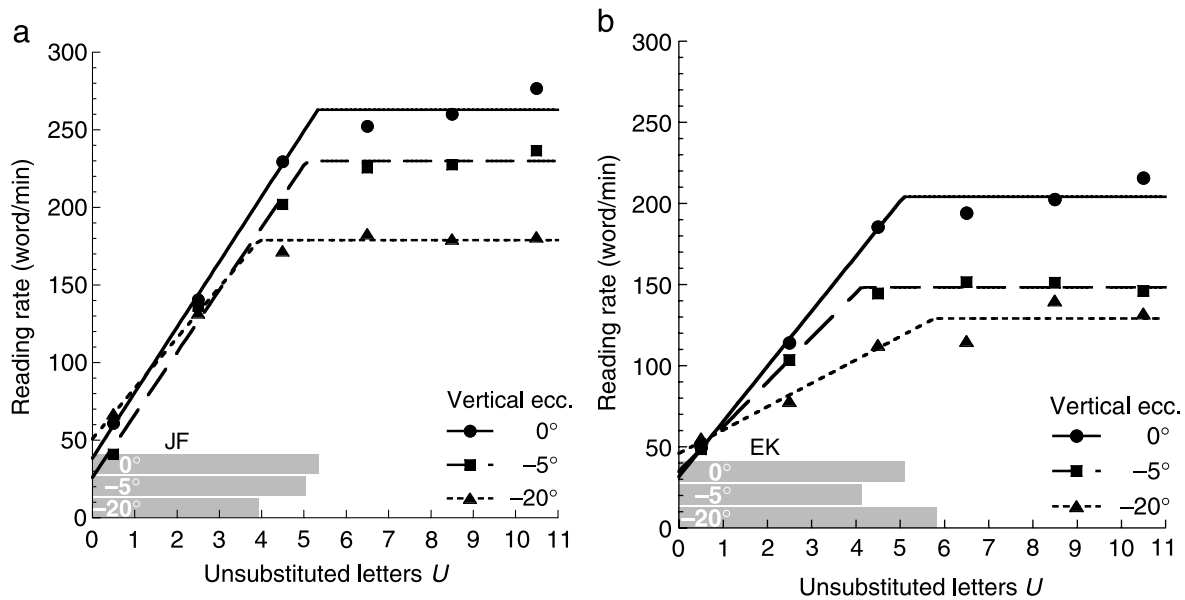


Figure 17. Substitute the letters. Reading rate as a function of the number of unsubstituted letters, for two observers. We measure threshold reading rates for RSVP presentation of ordered text, centered on the vertical midline at each of three vertical eccentricities in the lower visual field. The unsubstituted window is  $(-U/2, U/2)$ , which is horizontally centered on fixation. The rectilinear curve is the fit by Equation 7. (a) For observer JF, the best-fitting value of uncrowded span  $u$  (indicated by a horizontal bar) is 5.3 at vertical eccentricity  $0^\circ$ , 5.1 at  $-5^\circ$ , and 3.9 at  $-20^\circ$ . (b) For observer EK,  $u$  is 5.1 at  $0^\circ$ , 4.1 at  $-5^\circ$ , and 5.8 at  $-20^\circ$ .

rate as a function of unsubstituted span. Reading rate rises linearly with unsubstituted span up to a span of 4 or 5 and then levels off, having achieved the maximum reading rate. For each eccentricity, the line through the data represents the least-squared-error fit by Equation 7. The fit has three degrees of freedom:  $r_0$ ,  $\rho$ , and  $u$ . The best-fitting value of  $u$ , indicated by the horizontal gray bar, ranges from 4 to 6.

Equation 7 is similar to Equation 3, substituting effective for actual uncrowded span.  $\rho$  is still the rate parameter and is the slope of the rise in Figure 17.

Note the nonzero reading rates, about 40 word/min, when the unsubstituted span is zero. That is because the substitution leaves some letters unchanged (Table 3). The 80% threshold criterion used in our experiments would be unattainable if the substitution knocked out reading completely.

This intervention measures the observer's uncrowded span for reading by determining what is the smallest unsubstituted span at the display that preserves reading rate. We do not assume that an unsubstituted span is a perfect simulation of all aspects of the observer's uncrowded span. It is enough to suppose that reading rate is determined by the smaller of the two.

### Pull the curtain

We also tested with a large unsubstituted window, so large that only one edge was in the display, and measured

performance as a function of the edge position. We call this a “curtain.” A right curtain exposes an unsubstituted window at the left with bounds  $(-\infty, U_R)$ , and a left curtain exposes a window at the right with bounds  $(U_L, \infty)$ . We measured reading rate as a function of edge position for both right and left curtains.

We fit the data with a formula that assumes that the reading rate is linearly related to the effective uncrowded span, which is the intersection of the uncrowded and unsubstituted spans,

$$r = r_0 + \rho \max\left(0, \min(u_R, U_R) - \max(u_L, U_L)\right), \quad (8)$$

where the uncrowded span has bounds  $(u_L, u_R)$  and the unsubstituted span has bounds  $(U_L, U_R)$ . We use Equation 8 to make one fit to all the data in one panel (right and left curtain for one observer at one vertical eccentricity). We plot the fit as two curves. The right curtain has  $U_L = -\infty$  and the left curtain has  $U_R = \infty$ . The estimated  $u$  is 5.3 at vertical eccentricity  $0^\circ$ , 3.6 at  $-5^\circ$ , and 2.6 at  $-20^\circ$  for JF; 3.8 at  $0^\circ$ , 3.6 at  $-5^\circ$ , and 4.5 at  $-20^\circ$  for EK; 6.9 at  $0^\circ$ , 7.7 at  $-5^\circ$ , and 4.9 at  $-20^\circ$  for KAT.; and 7.1 at  $0^\circ$ , 7.4 at  $-5^\circ$ , and 4 at  $-20^\circ$  for NB.

Having measurements for both the right and the left curtains strengthens the conclusions. Since each block used only a right (or left) curtain at one position, one can imagine that observers might shift their fixation or attention away from the curtain to concentrate on the window. The temptation is in opposite directions for left and right

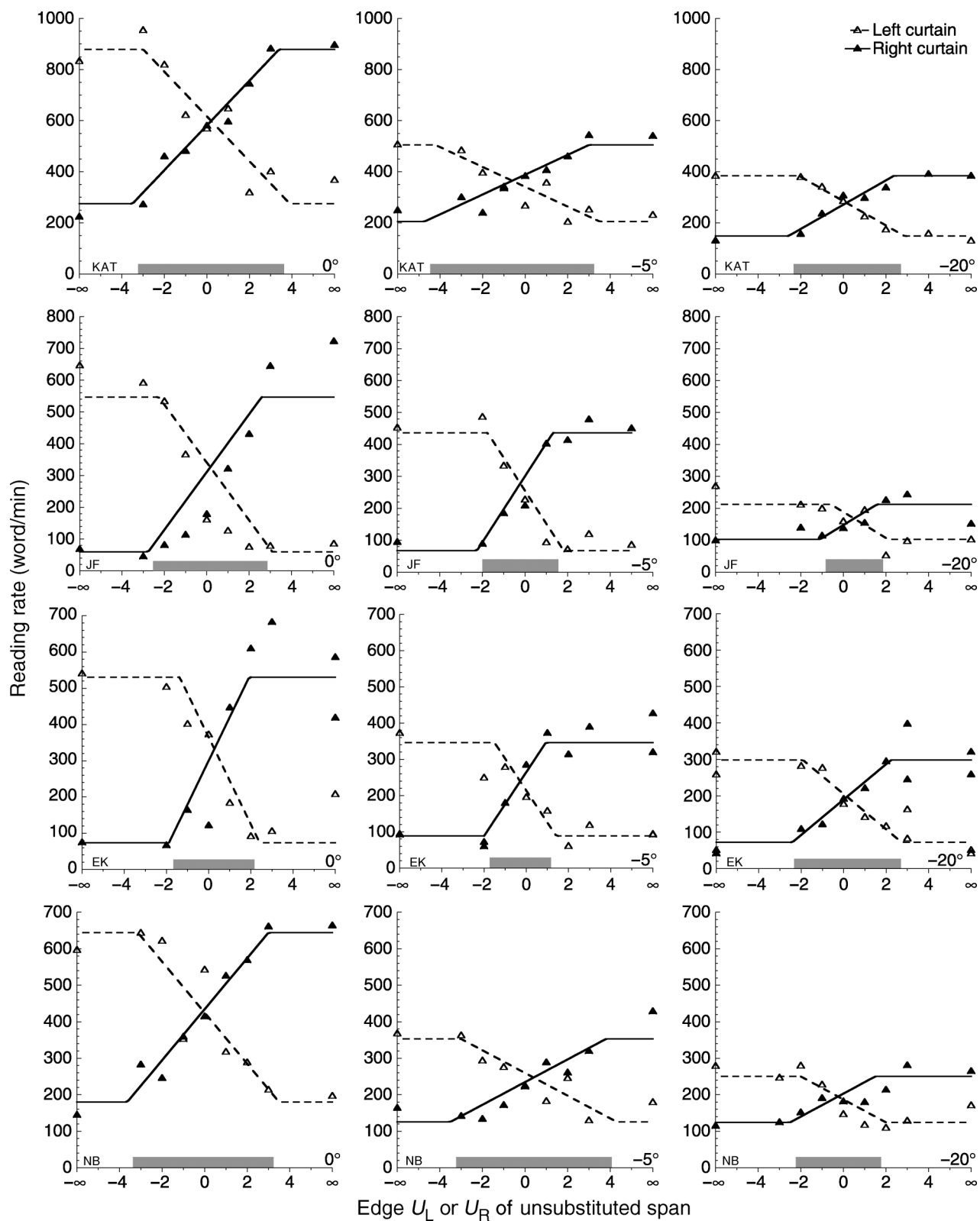


Figure 18. Pull the curtain. Reading rate as a function of the horizontal position (number of letters to the right of fixation) of the edge of the unsubstituted span. We measure threshold reading rate. The unsubstituted span has bounds ( $U_L$ ,  $U_R$ ). We call this condition “right curtain” when  $U_L = -\infty$  and “left curtain” when  $U_R = \infty$ . The solid and dashed lines are the fit by Equation 8. The gray bar is the estimated uncrowded span, with bounds ( $u_L$ ,  $u_R$ ). The observer and the vertical eccentricity are indicated to the left and right of the gray bar.

curtains with the same edge position. The right-curtain method would tend to shift the span leftward, and the left-curtain method would tend to shift the span rightward. In Figure 18, reading rate rises or falls with slope  $\pm\rho$  across the span. The left- and right-curtain data provide independent estimates of the span, and they agree.

### Compare the spans

Having measured each observer’s uncrowded span for reading, we ask how it compares to our estimate of uncrowded span for letter identification. Earlier, we fit

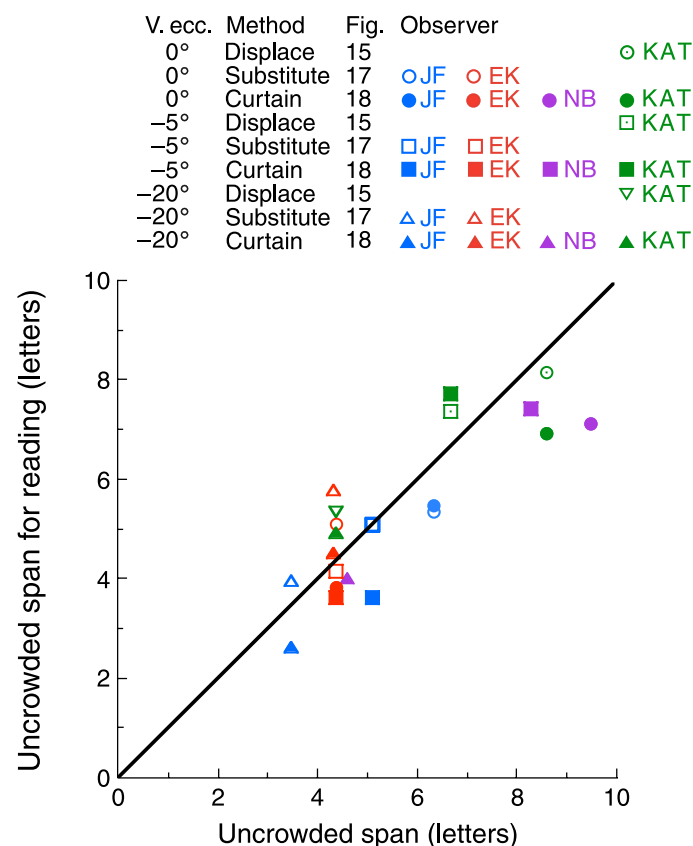


Figure 19. Compare the spans. Uncrowded span for reading is plotted as a function of uncrowded span for letter identification for four observers at three vertical eccentricities: 0°, -5°, and -20°. The span for reading is measured as a function of: 1. the horizontal position of a four-letter word (Fig. 15, “Displace”); or 2. the number of unsubstituted letters (Fig. 17, “Substitute”); or 3. the left or right edge position of a large unsubstituted window (Fig. 18 “Curtain”). For JF, EK, and KAT, the letter-identification span is estimated by Equation B10 from the values of  $b$  (Fig. 9) obtained by fitting Bouma’s law to measured critical spacings for letter identification (Fig. 8), as explained in the Methods section. For NB, the letter-identification span was measured directly, as explained in the Methods section. The reading and letter-identification uncrowded spans are nearly equal (the diagonal line). The RMS error is 1.0 letter.

Bouma’s law to our measurements of proportion correct letter identification (Fig. 8) to get Figure 9, which shows how  $b$  depends on eccentricity for each observer. From  $b$  we now calculate the uncrowded span for letter identification (Eq. B10) for each observer at each eccentricity. Figure 19 is a scatter diagram, plotting span for reading versus span for letter identification. Each point represents one observer at one eccentricity assessed by one of the three reading experiments. All the data points lie near the line of equality, across four observers, three vertical eccentricities (0°, -5°, and -20°), and three methods of measuring reading span.

The horizontal and vertical axes of Figure 19 are independent measures, based on very different tasks (letter identification and reading) applied to the same observer and vertical eccentricity. O’Regan (1990) would call the vertical scale a “perceptual” span because it is based on words, and the horizontal scale a “visual” span, because it is based on letters. Their equality is evidence that crowding imposes the same restrictive window—the uncrowded span—on reading and letter identification.

Three different methods indicate that observers really do read through a restrictive window equal to the uncrowded span (Fig. 5). When crowding is simulated by letter substitution, reading rate (over baseline) is proportional to the residual span that is both uncrowded and unsubstituted.

This is the first strong evidence in favor of Legge’s conjecture that reading rate is proportional to visual span. Visual span is the uncrowded span, determined solely by Bouma’s critical spacing.

Thus, both in the cliff and the plateau, crowding limits reading.

## Discussion

### Proportionality versus correlation

We credit Legge for the conjecture that reading rate is proportional to visual span. However, Legge and his collaborators have proposed an evolving series of ideas, and the most recent is incompatible with the first. Legge et al. (1997b) presented the Mr. Chips model of reading (maximum likelihood word choice limited by the visual span profile) and found that its average saccade length is the visual span plus 1. Since the saccade rate of reading is about 4 Hz, over a wide range of conditions, this implies that reading rate is proportional to visual span plus 1. However, 1 is small relative to the typical span, and it is hard to measure span with a precision better than 1, so we overlook it, taking their suggestion to be that reading rate is proportional to span. Similarly, in their Experiment 1, Legge et al. (2001) assumed proportionality and estimated the time per character.

In subsequent papers, Legge and his collaborators retreated from this strong conjecture (proportionality) to the weaker “visual span hypothesis” that “the visual span is an important factor that limits reading speed” (Chung, Legge, & Cheung, 2004; Legge, Ahn, Klitz, & Luebker, 1997a; Legge et al., 2001; Yu, Cheung, Legge, & Chung, 2007).<sup>7</sup> The idea is that the effects of many sensory manipulations on reading rate are mediated by changes in the visual span. These papers find a correlation between log reading rate and visual span, and note that such correlation is consistent with the visual span hypothesis. Anything less than a strong correlation would decisively reject the visual span as mediator. However, a strong correlation only weakly endorses the visual span’s role as mediator because changes in reading rate and visual span could be independent consequences of the same sensory manipulation. Furthermore, finding a strong correlation is much weaker than demonstrating proportionality. Proportionality means  $y = ax$ , which has only one degree of freedom,  $a$ . Correlation merely indicates that the data can be fit with a line  $y = ax + b$ , which has two degrees of freedom,  $a$  and  $b$ . In this special issue, Legge et al. (2007) go further, observing that five experiments yield the same slope of log reading rate versus visual span (0.14 log unit per character or 0.03 log unit per bit).

Might their data help us decide between conjectures? The original Legge conjecture is that reading rate is proportional to span,

$$r = \rho u, \quad (9)$$

where  $\rho$  is a fitted constant. The recent Legge conjecture is that log reading rate is linearly related to span,

$$\log r = \alpha u + \beta, \quad (10)$$

where  $\alpha$  and  $\beta$  are fitted constants. If we insist that the model predict zero reading rate when the span is zero, then we must reject the recent conjecture because it predicts a nonzero reading rate when the span  $u$  is zero. Setting that problem aside, we combined all the rates from Figure 5 of Legge et al. (2007). To fit Legge’s recent model, we plot their data as  $\log r$  versus  $u$  (not shown), and a linear regression yields  $\log r = 0.121u + 0.90$ ,  $R^2 = 0.89$ , which agrees with their fits.<sup>8</sup> To fit Legge’s original model, we plot log reading rate versus log span. Fitting with a unit-slope line yields  $\log r = 0.90 + \log u$ ,  $R^2 = 0.80$ . This is proportionality:  $r = 8u$  (Eq. 9). The recent

<sup>7</sup>These papers mostly report visual span in bits, instead of characters, but you can convert from bits to characters by dividing by the number of bits (4.7) per reliably recognized character (Legge et al., 2007).

<sup>8</sup>Reading rate  $r$  is characters per second and the span  $u$  is characters, where one perfectly recognized character corresponds to 4.7 bits in their bit-based measure of span.

model accounts for slightly more variance (0.89 versus 0.80) but has two degrees of freedom instead of one, and, as noted above, erroneously predicts a useful reading rate (79 word/min) at zero span. On balance, this favors the original Legge conjecture:  $r = \rho u$ .

We cannot explain yet why reading rate (and the parameter  $\rho$ ) drop with eccentricity. It is a burning issue, partly because of the practical consequences for readers with central field loss. It might seem that Legge’s visual span had solved it. Legge et al. (2001) say, “We conclude ... that shrinkage of the visual span results in slower reading in peripheral vision,” but in fact they only showed a correlation between reduced visual span and reduced reading rate. Our results replicate theirs in finding a tendency for visual span to shrink at greater eccentricity, but there are large individual differences, and for only one of Legge’s and none of Chung’s or our observers was the shrinkage sufficient to account for the slower reading at greater eccentricity (Figs. 9 and 13). As noted above, Legge et al. (2007) find a consistent slope of log reading rate versus visual span in five experiments, but this slope is too shallow, by a factor of five, to account for the effect of eccentricity on reading rate shown in their Figure 2.

In sum, the uncrowded span model has only two parameters,  $b$  and  $\rho$ , which control the critical spacing and maximum reading rate. Legge and his collaborators have suggested that reading farther out in the periphery reduces visual span enough to account for the reduction in reading rate. Here we show that the visual span is the uncrowded span  $u = 1 + 2/b$ . We document an unexpected dependence of  $b$  on eccentricity and striking variation among observers. We find that  $b$  grows with eccentricity, differently for each observer, but rarely grows enough to account for much of the sixfold reduction in maximum reading rate from  $0^\circ$  to  $-20^\circ$  vertical eccentricity, disappointing the hope expressed by Legge. For most observers, most of the drop in reading rate with eccentricity is accounted for by the rate parameter  $\rho$ , not the uncrowded span  $u$ .

Let us take a step back to see the big picture. This paper is focused on determining precisely how reading rate depends on span. Legge’s several conjectures bear on this, but that was not his focus. Legge’s recent papers, instead, have systematically characterized the effects of sensory parameters and learning on reading rate, showing that most of these effects seem to be mediated by changes in the visual span. For their purpose, it makes little difference whether it is reading rate or log reading rate that is linearly related to span. Their focus was simply to establish a functional link. The results of their work and ours are complementary. Our work, especially the letter substitution experiments, specifies the functional form, endorsing the original Legge conjecture of proportionality. Legge’s recent papers have breadth, exploring a wide range of conditions, indicating that the effects of contrast, spacing, size, and learning are mediated by changes in the span, while the effect of eccentricity is not.

## Ordinary reading is similar

In our experiments, words were presented serially (RSVP), minimizing eye movements. In daily life, text is static and people read by moving their eyes. Eye movements are an important part of ordinary reading, but the aspects of reading affected by crowding seem to be very similar when measured with and without eye movements.

In the “Plateau is crowded” section, we used a refined version of the Underwood and McConkie (1985) unsubstituted window technique. In both their study and ours, the letter substitutes were chosen so as to preserve word shape. Using RSVP, our estimates of span (at 0° vertical eccentricity) were about  $6 \pm 2$ , across four observers. Like us, Underwood and McConkie used a window that extended indefinitely left or right, but they tested only a few window-edge locations, which provide only an upper bound on span. However, in a following study using the same technique, Underwood and Zola (1986) found that good readers “used letter information as far from the center of fixation as at least 2 characters to the left” and 5 or 6 to the right. Their span extends two or three characters further to the right than ours. However, their criterion for using letter information was a statistically significant change in fixation duration (about 10%), which is less stringent than the roughly 15% of reading rate that each uncrowded letter position accounts for in our fits. Their less stringent criterion would tend to make their span estimate larger than ours.

Seizing the bull by its horns to directly compare ordinary and RSVP reading, Yu et al. (2007) compare reading rate as a function of text size for text presented dynamically, one word at a time (RSVP), or statically, all together (static flashcard with four lines of text). RSVP reading is faster (1.4×) but the log reading rate curves are parallel, showing the same dependence on spacing. In particular, the critical print size is equal for the two reading tasks, with an RSVP:flashcard ratio of  $0.98 \pm 0.04$  across five observers (Yu et al., 2007, their Table 2). This indicates that re-doing our experiments with ordinary reading would yield very similar results and the same conclusions.

## The uncrowded window

Figure 5 illustrates the idea of the uncrowded window, as applied to reading. However, like Bouma’s law, the uncrowded window applies to object recognition in general. Most objects are susceptible to crowding and have a spacing (internal among parts or external to other objects) that must exceed the observer’s local critical spacing if the object is to be recognized. This seems to correspond to the common distinction made between central (or “foveal”) viewing and peripheral viewing.

The center is uncrowded and the periphery is crowded. The retina is not dichotomous (critical spacing grows proportionally) but, for a given spacing, crowding is dichotomous, absent inside the uncrowded window and

ubiquitous outside it. Crowding depends solely on the ratio of actual to critical spacing, so words and other objects are uncrowded when the ratio exceeds 1 and crowded when the ratio is less than 1. This divides the visual field into an uncrowded center and a crowded periphery, with a fairly abrupt transition at the border (Fig. 8). The border between the uncrowded and crowded visual fields is not fixed on the retina. It depends on the spacing of the things being viewed. In reading, the spacing of the text determines where that boundary falls, and thus the size of the uncrowded window.

## Recap

We prove that the visual span is the uncrowded span (the number of characters that are not crowded) and that, for each observer, at each vertical eccentricity, reading rate is proportional to the uncrowded span.

## Conclusions

We show that Bouma’s law of crowding predicts an uncrowded central field through which we can read, and a crowded periphery through which we cannot (Fig. 5). This follows directly from Bouma’s observation that the critical spacing of crowding depends on the distance of the target from fixation.

The “visual span” is the number of characters that one can read without moving one’s eyes. Legge has suggested that reading rate is proportional to the visual span. We show that the visual span is the uncrowded span, ruling out the alternative explanations. This joins Bouma’s law and Legge’s conjecture to create the uncrowded span model of reading rate, the first account of how rate depends on letter spacing. The model—that reading rate is proportional to the uncrowded span—fits existing data well, over a wide range of spacings, sizes, and eccentricities.

To prove the uncrowded span model, we compare two very different tasks: reading text and identifying a letter. In reading, the observer processes a continuous stream of words, while in letter identification the observer categorizes a single simple shape. We measure the span for reading in three ways and find that it equals the span for letter identification. To prove that reading rate is proportional to the uncrowded span, we use silent substitution of letters to simulate crowding. We measure reading rate as a function of this unsubstituted span. The results show that we read through the uncrowded window and that reading rate is proportional to its span (in characters).

Our results are valid for ordinary conditions: well-corrected fluent observers reading ordinary text with adequate light. More generally, it seems that the visual span is the uncrowded span—reading rate depends on spacing and is independent of size, contrast, and lumi-

nance—if and only if the text contrast is at least four times the threshold contrast for an isolated letter.

Our claim that crowding limits reading once seemed untenable. In the plateau of the reading rate curve, increasing the spacing should relieve crowding yet fails to improve reading rate. This seeming paradox is resolved by noting that crowding is not homogeneous within a word.

Eccentricity remains a mystery. The rate factor relating reading rate to span depends strongly on eccentricity. Reading is slower at greater eccentricity.

Finally, although this paper is about reading, and Bouma’s original observations were about letters, his law applies to objects in general (Pelli et al., 2004). The critical spacing of facial features that makes it possible to recognize a face is equal to the critical spacing of letters that makes it possible to recognize a word (Martelli et al., 2005). Objects, such as words and faces, which require recognition of parts (like letters and facial features), can only be recognized when those parts are separated by at least the critical spacing. Thus, for any given spacing of parts, there will be an uncrowded central field through which the object can be recognized and a crowded periphery through which it cannot (Fig. 5).

## Methods

These methods apply to Figures 1–19. Appendix D has its own methods section.

### Observers

Four observers, EK, JF, KAT, and NB (ages 19–23), participated in the experiments. All observers had normal or corrected-to-normal vision and were fluent in English. All observers gave informed consent. Observers KAT and JF are authors. Observer EK here is not the same EK whose data appear in Pelli and Tillman (2007).

### Apparatus

Stimuli were generated on a Macintosh PowerPC computer running MATLAB with the Psychophysics Toolbox

(Brainard, 1997; Pelli, 1997). Several CRT displays were used, but we believe that the differences in luminance, frame rate, and resolution did not affect our results.

### Fixation

On all peripheral viewing tasks, we asked observers to fixate a mark on the screen. We watched their eyes, discarding the rare trials in which fixation was not maintained.

### Critical spacing (Fig. 6)

We mapped out the isolation fields shown in Figure 6 for one observer, KAT, with normal vision. The stimulus was a letter triplet. Each letter was randomly selected from nine characters, **DHKNORSVZ**, of the Sloan font (available at <http://www.psych.nyu.edu/pelli/software.html>). (The Sloan font was displayed bold, which increased the stroke thickness by 15%.) Background luminance was 12 cd/m<sup>2</sup>. Target (middle) and flanker letters were displayed at 90% contrast. Letters were light on a dark background. Three letter sizes, scaled for radial eccentricity, were tested at each horizontal position (Table 1). The observer clicked the mouse to begin each trial. Triplets were displayed at vertical eccentricities of 0° or –5° (lower visual field) at horizontal eccentricities of 0°, 6°, or 12° (right visual field). The viewing distance was 120 cm for stimuli presented at horizontal eccentricities of 0° and 6° and 80 cm at 12°.

The two flanking letters were displaced horizontally to the left and right of the target (0°), vertically above and below the target (90°), or along an intermediate angle (see Table 1). Despite the various angles of flanker displacement (“triplet orientation”), all the letters were always upright.

The target and flankers were displayed for 200 ms, followed by a response screen showing all nine possible characters. The observer’s task was to identify the just-seen target by clicking on the corresponding character in the response screen. Correct responses were rewarded by a beep. The observer clicked the mouse again to begin the next trial. Forty trials (in a block) yielded a threshold estimate. QUEST (Watson & Pelli, 1983) adjusted the letter spacing to home in on the center-to-center spacing

Vertical eccentricity	Horizontal eccentricity	Radial eccentricity	Letter sizes (deg)	Triplet orientations (deg)
0°	6°	6°	0.3, 0.43, 0.55	0, 45, 90, 135
0°	12°	12°	0.55, 0.83, 1.2	0, 45, 90, 135
–5°	0°	5°	0.3, 0.43, 0.55	0, 90
–5°	6°	7.8°	0.43, 0.55, 0.83	0, 40, 90, 130
–5°	12°	13°	0.83, 1.2, 1.5	0, 23, 45, 90, 113, 130

Table 1. Triplet conditions used in Figure 6. The target and flanker letters were of the same size and always vertical, as in Figure 3. Triplet “orientation” is the angle of the two flanker locations relative to horizontal.

required to yield 80% correct identification of the central letter. Points on the graph indicate the positions of the centers of the flanker letters at threshold. Note that exactly two flankers were present in each presentation, and they were always displaced in opposite directions, 180° apart. Thus, thresholds at displacement orientations  $x$  and  $x + 180^\circ$  are identical, by definition, and we plot the measured threshold at both points.

## Critical spacing (Figs. 8 and 9)

The methods for Figure 8 are similar to those for Figure 6. EK, JF, and KAT participated. The task was to identify the center letter in a triplet of lower case letters displayed in the Bitstream font “Courier 10 Pitch Bold.” Each target and flanker was a random sample from the 26 lowercase letters a–z. The two flankers were always displaced horizontally, to the right and to the left of the target letter. For each position in the visual field tested, letter-to-letter spacing and letter size were held constant (not varied as above). We used the same spacings as Legge et al. (2001) and also tried scaling spacing with vertical eccentricity (Table 2). As above, observers fixated a black square and the stimulus appeared for 200 ms. Observers responded by typing the appropriate letter on a keyboard. We measured proportion correct. For each condition, observers completed two runs of 40 trials each. Runs were completed in random order. Viewing distance was 60 cm for all runs except those in which either horizontal or vertical eccentricity was 20°. In 20° runs, viewing distance was reduced to 30 cm and the observer’s head was stabilized by a headrest (HeadSpot, University of Houston College of Optometry, <http://www.opt.uh.edu/uhcotech/Headspot/>).

Figure 8 shows measured proportion correct as a function of spacing for several observers, letter sizes, and positions in the visual field. (Similar results are also

Vertical eccentricity	Horizontal eccentricity	Radial eccentricity	Letter spacing (deg)
–5°	0°	5°	2.2, 2.75
–5°	2.5°	5.6°	2.2, 2.75
–5°	5°	7.1°	2.2, 2.75
–5°	10°	11.2°	2.2, 2.75
–10°	0°	10°	3.85, 4.4, 5.5
–10°	5°	11.2°	3.85, 4.4, 5.5
–10°	10°	14.1°	3.85, 4.4, 5.5
–10°	20°	22.4°	3.85, 4.4, 5.5
–20°	0°	20°	5.5, 8.8, 11
–20°	5°	20.6°	5.5, 8.8, 11
–20°	10°	22.4°	5.5, 8.8, 11
–20°	20°	28.3°	5.5, 8.8, 11

Table 2. Triplet conditions used in Figure 8. Letter size (x-height) was 0.9×spacing.

presented for three observers from Legge et al., 2001, as explained in the caption.) For each curve, the critical spacing is defined as the spacing yielding 80% correct. The data collected for Figure 8 allow us to estimate horizontal critical spacing, from which we estimate the radial critical spacing assuming an ellipticity of 2 (Appendix A).  $b$  is approximately the ratio of radial critical spacing to radial eccentricity (see Eq. 1). Thus, each curve in Figure 8 yields one point in Figure 9, the value of  $b$  at a particular eccentricity. Figure 9 shows linear regression lines ( $b$  vs. radial eccentricity  $\varphi$ ) for each observer. Each line corresponds to Equation 2 of the generalized Bouma law,  $b = b_1 + b_2\varphi$ , and is specified in the lower right of each graph in Figure 8. Figure 8 plots proportion correct as a function of spacing relative to the spacing predicted by the Bouma law, using the given  $b$  formula to specify how that observer’s  $b$  depends on eccentricity.

## Uncrowded span for letters (Fig. 19)

The horizontal scale in Figure 19 is the uncrowded span  $u$  for each observer and vertical eccentricity. For observers JF, EK, and KAT,  $u$  was calculated from that observer’s  $b$  formula in Figure 8, as follows. As explained in Appendix B, for a given vertical eccentricity, the uncrowded span is defined by the letter positions,  $-\varphi_h$  and  $\varphi_h$ , at the critical spacing. Initially we take the vertical eccentricity as a rough approximation of the radial eccentricity and calculate an approximate  $b$  (Eq. 2). Using this approximate  $b$  and the given values for vertical eccentricity and letter spacing, we calculate an approximate horizontal eccentricity  $\varphi_h$  for the right end of the uncrowded span (Eq. B3), from which we calculate an approximate radial eccentricity  $\varphi$  (Eq. A2), from which we re-calculate  $b$  accurately (Eq. 2). We then retrace our steps, using this accurate  $b$  to obtain an accurate  $\varphi_h$  from which we calculate the uncrowded span  $u$  (Eq. B10). (Note that the simpler Eq. B4 gives practically the same answer as Eq. B10.)

We measured at many vertical eccentricities, but not at 0° (Table 2). Our estimated spans at 0° (about 7) are based on extrapolations from larger vertical eccentricities and are somewhat lower than measured values (about 10, Legge et al. 2001), suggesting that 0° vertical eccentricity is special.

Observer NB’s uncrowded span for letters was measured directly. Instead of collecting the entire psychometric function as in Figure 8, for each vertical eccentricity (0, –5°, and –20°) we used QUEST to home in on the threshold horizontal eccentricity yielding 80% correct identification of the target. At each vertical eccentricity, separate horizontal eccentricity thresholds were obtained for the left and right visual fields. Each run consisted of 100 trials, including 50 in which the stimulus appeared on the right and 50 in which the stimulus appeared on the

left. Left and right trials were randomly interleaved, in order to encourage the observer not to shift his or her attention to one side. In Figure 19 (horizontal axis), we plot NB’s uncrowded span  $u = 1 + (\phi_R - \phi_L)/s$ .

In order to best match the reading measurements described below, the letters were displayed in lowercase in the Linotype font Helvetica Neue LT 85 Heavy. At vertical eccentricity 0°, the x-height was 0.5°, center-to-center letter spacing was 0.625°, and the viewing distance was 100 cm. At vertical eccentricity -5°, x-height was 2°, letter spacing was 2.5°, and viewing distance was 40 cm. At vertical eccentricity -20°, x-height was 8°, letter spacing was 10°, and viewing distance was 10 cm. The headrest was used at 10 cm viewing distances.

### Reading (Figs. 15–19)

Text was displayed in lowercase in the Linotype font Helvetica Neue LT 85 Heavy. For central reading (0° eccentricity), observers were asked to fixate midway between two black squares (0.2°) centered 0.9° above and below the center of the word. For peripheral reading (-5° and -20° vertical eccentricity), observers fixated a single black square (0.2°) positioned above the center of the word.

At 0° vertical eccentricity, the x-height was 0.5°, center-to-center letter spacing was 0.625°, and the viewing distance was 100 cm. At -5° vertical eccentricity, x-height was 2°, letter spacing was 2.5°, and viewing distance was 40 cm. At -20° vertical eccentricity, x-height was 8°, letter spacing was 10°, and viewing distance was 10 cm. The headrest was used at 10 cm viewing distances.

Under all conditions, spatial and temporal flankers were added to words to minimize end effects. In the displacement and substitution experiments, spatial flankers were random letters presented on either side of the word, as in **awordb**. In the curtain experiments, all flankers were the letter “x,” as in **xwordx**. The temporal flankers are a random string of letters presented before the first word and another after the last word in each trial, with presentation times identical to the target words. Observers were instructed to ignore the spatial and the temporal flankers.

Reading rate was measured using RSVP (Potter, 1984). In RSVP reading, words are presented serially, one after another, centered at the same location. Reading rate is defined as the rate at which words are presented. We used the QUEST adaptive staircase procedure (Watson & Pelli, 1983) to measure threshold RSVP reading rate for each condition. In each trial, observers were shown six words. Observers read the six words out loud with unlimited speaking time. 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 80% accuracy.

### Displace the word (Fig. 15)

To measure observer KAT’s uncrowded spans at 0°, -5°, and -20°, we measured the threshold reading rate for four-letter words centered at 0, 1, 2, 3, 4, 5, 6, 7, or 8 letter spaces to the right of fixation. The set of possible stimuli contained all 1708 four-letter words in the Kucera and Francis (1967) corpus. Each word was drawn randomly from the list. Her uncrowded span  $u$  was estimated by fitting Equation 6 to her data.

### Substitute the letters (Fig. 17)

Observers JF and EK read text from the murder mystery novel *Loves Music, Loves to Dance* by Mary Higgins Clark (1991). The text has a 7.5 Fog index and 5.5 Fleish–Kincaid Index. The text was not altered prior to experimental manipulations. No observer read the same passage twice.

We measured the uncrowded span using letter substitution at three vertical eccentricities, 0°, -5°, and -20°. Crowding impairs letter identification but spares holistic word recognition (Pelli & Tillman, 2007). Thus, substituting letters within a word roughly simulates crowding for the substituted letters provided the substitution can be made without affecting word shape. We used a

Original	Substitutes	Original	Substitutes
a	a e	A	A
b	b h	B	B P R
c	c e	C	C G
d	d	D	D
e	a c e	E	E F
f	f	F	E F
g	g	G	C G
h	b h	H	H
i	i	I	I L
j	j	J	J
k	k	K	K
l	l	L	I L
m	m	M	M
n	n r	N	N
o	c o	O	O Q
p	p q	P	B P R
q	p q	Q	O Q
r	n r	R	B P R
s	s	S	S
t	t	T	T
u	u	U	U
v	v	V	V
w	w	W	W
x	x	X	X
y	y	Y	Y
z	z	Z	Z

Table 3. Letter substitutes (Figs. 16 and 17). Each letter is replaced by one of its substitutes, randomly selected.

Original	Substitutes	Original	Substitutes
a	a e	A	A
b	b h	B	B P R
c	c e	C	C G
d	b d h	D	D
e	a c e	E	E F
f	f t	F	E F
g	g	G	C G
h	b h	H	H
i	i	I	I L
j	j	J	J
k	k	K	K X
l	l	L	I L
m	m	M	M
n	n r	N	N
o	c o	O	O Q
p	p q	P	B P R
q	p q	Q	O Q
r	n r	R	B P R
s	s	S	S
t	f t	T	T
u	u	U	U
v	v	V	V X Y
w	w	W	W
x	x	X	K V X Y
y	y	Y	V X Y
z	z	Z	Z

Table 4. Letter substitutes (Fig. 18). Each letter is replaced by one of its substitutes, randomly selected. Table 4 is very similar to Table 3. It was created using a slightly less stringent criterion for calling a pair of letters “indistinguishable when crowded,” allowing more substitutes.

discrimination test to determine appropriate substitutes: A pair of letters could be substituted for each other if they were indistinguishable when viewed peripherally with flanker letters on both sides. The letter substitutes used to collect the data in Figure 17 are listed in Table 3.

In each condition, we designated a certain span of letters, centered at fixation, as unsubstituted. All letters outside of this *unsubstituted span* were subject to substitution, as specified in Table 3.

We measured threshold reading rates at three different vertical eccentricities (0°, -5°, and -20°) with six different (average) unsubstituted spans (0.5, 2.5, 4.5, 6.5, 8.5, and 10.5 letters). Each word was centered on the vertical midline.

In each case the unsubstituted span was always a whole number of letters centered on fixation, and thus was even for even-length words and odd for odd-length words. For example, in one condition the span was 2 for even-length words and 3 for odd-length words, and the reading rate is plotted as a point at the average span, 2.5.

We measured reading rates two or three times for each condition and calculated averages. Observers performed the 18 conditions in random order. For each observer at

each eccentricity, the uncrowded span  $u$  was estimated by fitting Equation 7 to the results.

### Pull the curtain (Fig. 18)

All four observers participated in this experiment. The text again was taken from *Loves Music, Loves to Dance*. Observers who also participated in the substitution experiment did not re-read any passages they had already read. Letter substitutes were drawn from Table 4. Here we used a large unsubstituted window, so large that only one edge was in the display, and measured performance as a function of the edge position. We call this a “curtain.” A right curtain exposes a window at the left with bounds  $(-\infty, U_R)$ , and a left curtain exposes a window at the right with bounds  $(U_L, \infty)$ . We measured reading rate as a function of edge position for both right and left curtains.

Values of  $U_R$  tested were  $-\infty$  (all letters substituted),  $-2, -1, 0, 1, 2, 3$ , and  $\infty$  (no letters substituted). Values of  $U_L$  tested were  $-\infty$  (no letters substituted),  $-2, -1, 0, 1, 2, 3$ , and  $\infty$  (all letters substituted). In some cases, we also measured thresholds at  $U_R = -3$  and  $U_L = -3$ . Conditions were run in blocks, and blocks were run in random order. For each observer at each eccentricity, the uncrowded span  $u$  was estimated by fitting Equation 8 to the results.

## Appendix A: Critical spacing

The calculation of critical spacing and uncrowded span is intricate, but it rests on just one assumption: Bouma’s

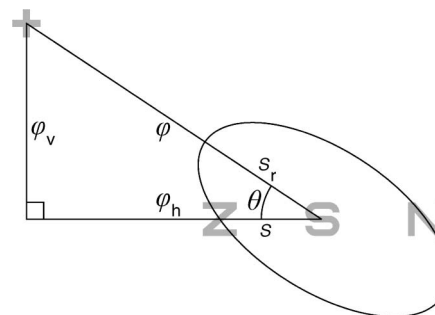


Figure A1. Critical spacing. The stimulus is shown here in gray to distinguish it from the black geometric diagram. The observer fixates the plus (top left). The target (S) is midway between two flankers (Z and N). The ellipse, centered at the target location, represents the critical spacing of the flankers from the target for this observer.  $\phi_h$  and  $\phi_v$  are the horizontal and vertical position of the target, relative to fixation.  $\phi$  is the radial eccentricity (distance from fixation) of the target.  $\theta$  is the angular tilt of the fixation-target line, relative to horizontal.  $s$  is the critical spacing measured horizontally.  $s_r$  is the critical spacing measured radially (i.e., toward fixation). The ellipticity  $\varepsilon$  of the ellipse (ratio of length to width) is 2.

law. [Appendix A](#) derives the cliff ([Eq. A6](#)) and [Appendix B](#) derives the plateau ([Eq. B8](#)).

Assembling the known facts of crowding (Bouma’s law), we now produce a formula for horizontal critical spacing at any location. The diagram ([Fig. A1](#)) illustrates the application of Bouma’s flanked letter paradigm to measure the horizontal critical spacing at an arbitrary location in the visual field: horizontal eccentricity  $\varphi_h$ , vertical eccentricity  $\varphi_v$ , and radial eccentricity  $\varphi$ . [Figure A1](#) shows, in gray, the fixation cross (upper left) and the location of the target (lower right). The target is at the center of an ellipse that represents the critical spacing for neighboring flankers. The experimenter typically chooses a fixed vertical eccentricity and measures the horizontal critical spacing  $s$  as a function of the horizontal eccentricity. (This approach omits in-out asymmetry, as explained in [Footnote 9](#).)

Bouma showed that critical spacing in the radial direction is proportional to radial eccentricity. Toet and Levi (1992) confirmed this at the moderate and large eccentricities that Bouma tested, but found that a small additive offset (insignificant at large eccentricity) is needed to describe critical spacing at small eccentricities,

$$s_r = s_0 + b\varphi, \quad (\text{A1})$$

where  $s_0$  is the critical spacing at zero eccentricity. Using a low threshold criterion, Toet and Levi found  $s_0$  to be about  $0.06^\circ$ ; using a higher criterion we find it to be about  $0.2^\circ$ . Pythagoras’s theorem relates the radial eccentricity to the horizontal and vertical eccentricities.

$$\varphi^2 = \varphi_h^2 + \varphi_v^2 \quad (\text{A2})$$

Toet and Levi (1992) measured critical spacing in all directions, confirming Bouma’s proportionality, and his observation that the critical spacing contour is roughly elliptical, with the major axis pointing to fixation.<sup>9</sup> The ellipticity  $\varepsilon$  (ratio of length to width) is about 2. Assuming such an ellipse, we can calculate the ratio of the major and

<sup>9</sup>Bouma (1970) noted an in-out asymmetry in crowding. Testing a peripheral target with a single flanker reveals that the critical spacing is smaller toward fixation than away from fixation. See Motter and Simoni (2007) for an explanation. That asymmetry is not captured by testing with symmetrically placed flankers ([Fig. 6](#) and Toet & Levi, 1992), but the in-out asymmetry is present in Bouma’s (1978, p. 24) sketch of the isolation fields. For simplicity, our elaboration of Bouma’s law omits the in-out asymmetry. The ellipticity is needed to accurately account for reading rate data, but the in-out asymmetry is not.

horizontal radii,  $s_r$  and  $s$ , as a function of the angle  $\theta$  between them,

$$\begin{aligned} \frac{s_r}{s} &= \sqrt{1 + (\varepsilon^2 - 1)\sin^2\theta} \\ &= \sqrt{1 + (\varepsilon^2 - 1)\frac{\varphi_v^2}{\varphi^2}} \end{aligned} \quad (\text{A3})$$

Dividing [Equation A1](#) by [Equation A3](#) achieves our goal: a formula for the horizontal critical spacing at an arbitrary location,

$$s = \frac{s_0 + b\varphi}{\sqrt{1 + (\varepsilon^2 - 1)\frac{\varphi_v^2}{\varphi^2}}}. \quad (\text{A4})$$

This would collapse down to [Equation A1](#) if the ellipse were a circle ( $\varepsilon = 1$ ).

The derivation of [Equation A4](#) is pure geometry, but a minor ad hoc modification improves its empirical accuracy by abolishing the orientation dependence at zero eccentricity, as found by Toet and Levi (1992),

$$s = s_0 + \frac{b\varphi}{\sqrt{1 + (\varepsilon^2 - 1)\frac{\varphi_v^2}{\varphi^2}}}. \quad (\text{A5})$$

This replaces [Equations A3](#) and [A4](#).

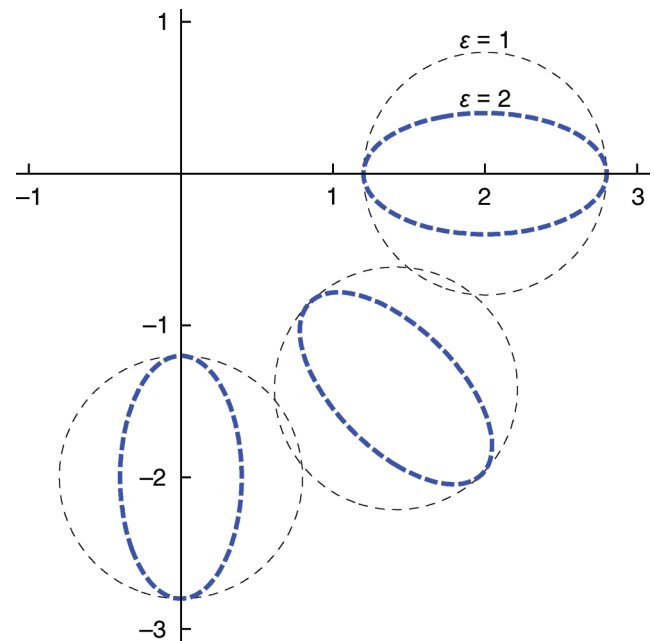


Figure A2. The critical spacing in all directions (as in [Figs. 3](#) and [6](#)) for three target locations and two degrees of ellipticity  $\varepsilon = 1$  (thin gray) and 2 (thick blue), given [Equation A1](#),  $s_0 = 0.2^\circ$ , and  $b = 0.3$ . The axes are horizontal  $\varphi_h$  and vertical  $\varphi_v$  position in the visual field, relative to fixation.

The *critical spacing for reading* is the smallest critical spacing at the given vertical eccentricity, which is at the vertical midline,  $\varphi_h = 0$ , so it is

$$s = s_0 + \frac{b\varphi_v}{\varepsilon} \quad \text{if } \varphi_h = 0. \quad (\text{A6})$$

Given Equation A1 and ellipticity, Figure A2 plots the critical spacing in all directions for three target locations and two degrees of ellipticity  $\varepsilon = 1$  (thin gray) and 2 (thick blue). The axes represent position (deg) in the visual field, relative to fixation.

## Appendix B: Uncrowded span

Here we use the formula for horizontal critical spacing derived in Appendix A to predict the uncrowded span as a function of letter spacing and vertical eccentricity.

The uncrowded span is the number of letter spaces that fit in the window extending from  $-\varphi_h$  to  $+\varphi_h$ . For a given vertical eccentricity  $\varphi_v$ , we select the horizontal eccentricity  $\varphi_h$  so that the given spacing  $s$  is the horizontal critical spacing at that location  $(\varphi_h, \varphi_v)$ . First we solve Equation A5 for (squared) radial eccentricity  $\varphi^2$ .

$$\varphi^2 = \frac{(s - s_0)^2}{b^2} \left( \frac{1}{2} + \frac{1}{2} \sqrt{1 + 4(\varepsilon^2 - 1) \frac{b^2 \varphi_v^2}{(s - s_0)^2}} \right) \quad (\text{B1})$$

Then we solve Equation A2 for horizontal eccentricity and plug in our expression for  $\varphi^2$ .

$$\begin{aligned} \varphi_h &= \sqrt{\varphi^2 - \varphi_v^2} \\ &= \sqrt{\frac{(s - s_0)^2}{b^2} \left( \frac{1}{2} + \frac{1}{2} \sqrt{1 + 4(\varepsilon^2 - 1) \frac{b^2 \varphi_v^2}{(s - s_0)^2}} \right) - \varphi_v^2} \\ &= \frac{s - s_0}{b} \sqrt{\frac{1}{2} + \frac{1}{2} \sqrt{1 + 4(\varepsilon^2 - 1) \frac{b^2 \varphi_v^2}{(s - s_0)^2}} - \frac{b^2 \varphi_v^2}{(s - s_0)^2}} \end{aligned} \quad (\text{B2})$$

Plotting Equation B2 as  $\varphi_h$  versus  $s$  produces a rising curve (not shown) that descends to the left, asymptotically vertical, and ascends to the right, asymptotically proportional to  $s$ . The curve is characterized by the two asymptotes. When the spacing is large, the window's extent is asymptotically proportional to the spacing,

$$\varphi_h \approx \frac{s}{b} \quad \text{if } s \gg s_0 + b\varphi_v, \quad (\text{B3})$$

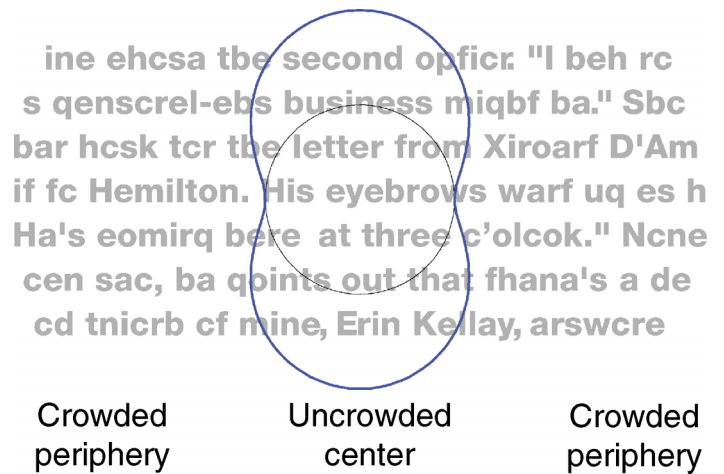


Figure B1. The uncrowded window, as in Figure 5. Fixation is at the center of the circle. Plotting  $\varphi_h$  versus  $\varphi_v$  (Eq. B2) traces out the boundary of the uncrowded window. The boundary is plotted for ellipticity  $\varepsilon = 1$  (thin gray) and 2 (thick blue), where  $s_0 = 0.2^\circ$ ,  $s = 1^\circ$ , and  $b = 0.3$ .

where  $\approx$  means asymptotically equal. The uncrowded extent  $\varphi_h$  shrinks to zero when the horizontal spacing is reduced to the horizontal critical spacing at the vertical midline, which is the critical spacing for reading (Eq. A6).

Plotting  $\varphi_h$  versus  $\varphi_v$  (Eq. B2) traces out the boundary of the uncrowded window (Fig. B1). When there is no ellipticity ( $\varepsilon = 1$ ) this boundary is a circle, as in Figure 5, and the gray circle in Figure B1. Increasing the ellipticity ( $\varepsilon = 2$ ) makes the isolation fields narrower (Fig. A2), better able to isolate letters above and below fixation, so the uncrowded window extends further up and down, as shown by the thick blue hourglass boundary in Figure B1.

## Uniform angular spacing at the observer's eye

If we have uniform angular spacing of the letters (as if printed on the inside of a large sphere centered on the observer), then the uncrowded interval is  $(-\varphi_h/s, \varphi_h/s)$ , with a *breadth*, left to right, of  $2\varphi_h/s$ . The span is slightly larger. By tradition, *span* refers to the number of letters acquired. Our interval extends from the center of the leftmost uncrowded letter to the center of the rightmost uncrowded letter. The span includes the whole of those letters and thus extends half a letter further to the left and right, so the span equals the interval's breadth plus one. (Except, of course, that when no letter is uncrowded the span and breadth are both zero.) Thus, the uncrowded span  $u_o$  is

$$u_o = 1 + \frac{2\varphi_h}{s}, \quad (\text{B4})$$

where the ball-shaped “o” subscript is a reminder that we assumed uniform angular spacing.

As a predictive factor for reading rate (i.e., what to use in Eq. 1), we see little to choose between breadth and span (i.e., breadth+1). The equation for breadth is simpler. The +1 needed for span is a fussy detail of little consequence. However, it is important to us, here, that the model should accurately incorporate the Legge et al. (2001) conjecture. They said “span,” so we use span, but anyone who develops the uncrowded span model further may wish to substitute breadth for span in Equation 1 and thus drop the leading “+1” from Equations B4–B10. (Actually, to be precise, Legge et al., 1997b, suggested that reading rate is proportional to span+1, which we simplified to just span. Here we hold back from further substituting breadth for span, which is breadth+1, but future authors may be more daring.)

We use Equation B2 to substitute for  $\phi_h$ ,

$$u_o = 1 + \frac{2s - s_0}{b} \frac{1}{s} \times \sqrt{\frac{1}{2} + \frac{1}{2} \sqrt{1 + 4(\varepsilon^2 - 1) \frac{b^2 \phi_v^2}{(s - s_0)^2} - \frac{b^2 \phi_v^2}{(s - s_0)^2}}}. \quad (\text{B5})$$

If the spacing is large relative to the minimum critical spacing  $s \gg s_0$  then the span depends on spacing and eccentricity solely through the ratio of actual to critical spacing  $s/(b\phi_v)$ ,

$$u_o = 1 + \frac{2}{b} \times \sqrt{\frac{1}{2} + \frac{1}{2} \sqrt{1 + 4(\varepsilon^2 - 1) \frac{b^2 \phi_v^2}{s^2} - \frac{b^2 \phi_v^2}{s^2}}} \quad \text{if } s \gg s_0. \quad (\text{B6})$$

If the ellipse were a circle then this would collapse to a simpler expression:

$$u_o = 1 + \frac{2}{b} \sqrt{1 - \frac{b^2 \phi_v^2}{s^2}} \quad \text{if } \varepsilon = 1 \text{ and } s \gg s_0. \quad (\text{B7})$$

In general, when the ratio of actual to critical spacing is large,  $s \gg s_0 + b\phi_v$ , the uncrowded span (Eq. B5) asymptotically approaches a constant value, independent of spacing,

$$u_o \approx 1 + \frac{2}{b} \quad \text{if } s \gg s_0 + b\phi_v. \quad (\text{B8})$$

$b$  is typically around 0.4, so the added 1 is only a small fraction of the span value. The span  $u_o$  shrinks gradually

to 1 and then suddenly to zero when the horizontal spacing is reduced to the horizontal critical spacing at the midline (Eq. A6).

Ordinarily we read on the horizontal midline, which is the important special case of zero vertical eccentricity, for which Equation B5 collapses down to

$$u_o = 1 + \frac{2s - s_0}{b} \frac{1}{s} \quad \text{if } \phi_v = 0. \quad (\text{B9})$$

The cliff, at  $s_0$ , of the reading rate curve for zero vertical eccentricity produced by this equation (after multiplying by  $\rho$ ) is less steep than that produced by Equation B6 for nonzero vertical eccentricity. The lesser steepness is discernable in the curves plotted in Figure 12 for zero and nonzero vertical eccentricity.

## Uniform spacing in the page: Perspective compression

In defining  $u_o$  for Equation B4 above, we assumed a uniform angular spacing of the letters at the observer’s eye. However, most text displays, including the printed page, instead maintain a uniform spacing in the plane of the display, which we take to be orthogonal to the line of sight at fixation. This uncrowded span  $u$  is

$$u = 1 + \frac{2 \tan \phi_h}{\tan \phi_h - \tan(\phi_h - s)}. \quad (\text{B10})$$

This perspective compression is responsible for the droop of reading rate at large spacing (Figs. 1 and 12). For small angles (i.e., small horizontal eccentricity  $\phi_h$ ),  $\tan \phi_h \approx \phi_h$  so Equation B10 converges on Equation B4 and thus  $u \approx u_o$ .

## Conclusion

The complicated algebraic expressions above might make this all seem highly speculative. Not so. The only assumption is Bouma’s law, which has strong empirical support. The rest is geometry, and the answers are exact (Eqs. B5 and B10). The several approximations mentioned in passing are provided merely to aid the reader’s intuitions. All our fits use the exact Equation B10 (with dither, as described in Appendix C).

The usual intuition is that one can always increase spacing enough to escape from crowding. That is misleading when thinking about uncrowded span, as increasing letter spacing pushes the boundary further out but cannot eliminate crowding (see the “Inhomogeneity of crowding within a word” section). In fact, the uncrowded span—the number of letters—turns out to be asymptotically independent of spacing at large spacing. The same





laboratories for unordered text. Our ordered-text results replicate Chung (2002). Our new conclusions depend on our unordered-text results, which show excellent agreement among all three observers, authors and naive alike.

The stimuli were created by a Power Macintosh computer using MATLAB with the Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997). The background luminance of the CRT used to display the stimuli was 10 cd/m<sup>2</sup>. The display resolution was 1024 × 768 pixels at 75 Hz, 28 pixels/cm. The viewing distance was 23 cm for peripheral trials and 200 cm for foveal trials.

All texts were presented in the Courier font, black on a white background. Text was presented either foveally or –5° or –10° below fixation using RSVP. The texts were from *Reader’s Digest* (average Flesch–Kincaid grade level 11.0; Kincaid, Fishburn, & Chissom, 1975) and were shown in order or in scrambled word order. We will refer to text that preserves the original word order as *ordered* and to text with scrambled word order as *unordered*. See Table D1.

All texts were edited to remove uncommon words and names to enhance ease of reading. All punctuation was removed except for apostrophes. Words with dashes were separated and numerals were replaced by their corresponding word (“2” becomes “two”). [We now think that this editing made no difference to our results and suggest that future studies use unedited text.] The average word length was 5 characters. Each text sample was only used once per observer.

In foveal trials, the observer was asked to fixate between two points that appeared directly above and below the middle of the target word. For peripheral trials, the observer fixated on a horizontal line and the text was displayed 5° or 10° below the line, as in Chung (2002). In peripheral trials, the observer’s head was stabilized by a headrest (HeadSpot, University of Houston College of Optometry, <http://www.opt.uh.edu/uhcotech/Headspot/>). In both foveal and peripheral trials, the experimenter monitored the eyes of the observer to ensure that fixation was maintained. Letter size (x-height) and letter-to-letter spacing varied from run to run (Table D2).

Each run consisted of six trials and each trial presented 10 words. The observer clicked the mouse to begin the first ten-word trial. Each new trial began at the next word in the text beyond where the last trial ended. The text was displayed one word at a time at the appropriate location on the screen and the observer tried to read the words aloud with no time limit. The observer

Ordered	Unordered
It used to be that when I felt that way I'd just drink some coffee and presto energy	Just way coffee I'd to used presto I some that energy felt used be and that It when

Table D1. Text conditions.

Vertical eccentricity	Size (deg)	Spacing (deg)
0°	0.1	0.1
0°	0.16	0.07, 0.09, 0.14, 0.16, 0.28, 0.42, 0.56
0°	0.4	0.4
0°	1.6	1.6
–5°	0.5	0.5
–5°	0.7	0.7
–5°	1.6	1.6
–5°	3.5	3.5
–10°	1.4	0.7, 1.0, 1.4, 4.2, 5.6, 7.0
–10°	2.0	2.0
–10°	3.0	3.0

Table D2. Letter size (x-height) and center-to-center spacing.

clicked the mouse again to proceed to the next trial. A voice recorder taped the run and the experimenter later counted the number of words read correctly. Credit was given regardless of the order in which the words were reported. If the proportion correct for the run was less than 77% or greater than 83% the same condition was run again with a new text at a slower or faster presentation rate. Runs in which proportion correct was 77% to 83% correct were used to calculate the reading rate, i.e., the rate at which the reader is reading at approximately 80% correct. The reported reading rate counts only words read correctly (unlike the Methods for Figs. 13–18) and is based on the stimulus presentation time (as in Legge, Pelli, Rubin, & Schleske 1985), not the observer’s speaking time, which was much longer.

Lastly, we constructed psychometric functions by measuring proportion correct as a function of presentation rate (Fig. D2). For this, the text was presented in the fovea as 0.16° letters spaced 0.16° apart, center to center.

## Results

We measured the effect of letter spacing on reading rate for ordered and unordered words in the fovea and periphery.

For centrally presented ordered words (Fig. D1, 0° vertical eccentricity solid line), reading rate is independent of spacing provided the spacing exceeds the 0.16° letter size (vertical dotted line). Across three observers, the average reading rate ± standard error for text with nonoverlapping letters is 444 ± 55 word/min. At smaller spacings (less than 0.16°) the letters overlap and there is a threefold decline in reading rate. These results replicate Chung (2002), whose data are plotted in Figure D1 as red wedges.

As with centrally presented words, reading rate in the periphery (–10°) for ordered words is independent of spacing provided the letters do not overlap (Fig. D1, –10°

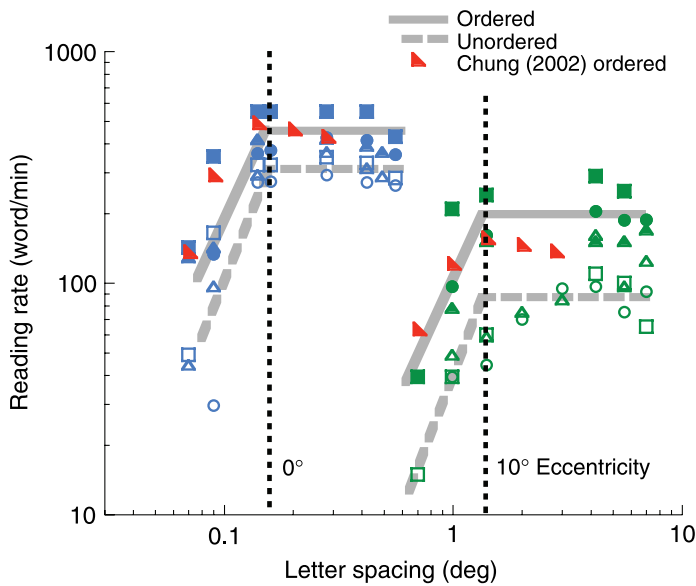


Figure D1. Ordered and unordered words at 0° and -10° vertical eccentricity. The vertical scale is the number of words (per minute of presentation time) that the observer correctly identified (in six 10-word trials). The horizontal scale is the center-to-center letter spacing. In this and other figures, squares indicate data from observer TDB, circles indicate MSX, and triangles indicate MAF. The red wedges are average reading rates from Chung (2002). We applied a two-line fit by eye (Chung, 2002). The solid line and solid symbols (including the wedges) represent ordered words; the dashed line and open symbols represent unordered words. The vertical dotted lines designate letter spacing equal to letter size (0.16° in the fovea and 1.4° in the periphery): letters overlap at smaller spacings. Reading rate for nonoverlapping letters is practically independent of spacing.

vertical eccentricity solid line). Peripheral reading at -10° of 1.4° nonoverlapping letters is half as fast as foveal reading of 0.16° nonoverlapping letters. The peripheral reading rate is  $184 \pm 28$  word/min across three observers. At smaller spacings (less than 1.4°), the letters overlap and there is a fourfold decline in reading rate. These results, too, replicate Chung (2002).

As Chung (2002) notes, the -10° peripheral reading rate is half the foveal rate despite her use of text larger than critical print size at both sites. Like her, we have no explanation for the peripheral drop, as the need for eye movement has been minimized by the use of the RSVP paradigm.

In the fovea, the reading rate for unordered words, as with ordered words, is independent of letter-to-letter spacing (Fig. D1, 0° vertical eccentricity dashed line) at all spacings larger than the letter size (0.16°). The reading rate plateau is  $297 \pm 15$  word/min for unordered words. The context gain is  $444/297 = 1.5$ . At vertical eccentricity -10°, the context gain is  $184/90 = 2$  or more for nonoverlapping letters.

Figure D2 shows the proportion of words presented that were correctly identified as a function of foveal presentation rate for each observer. The three observers perform very similarly reading unordered words (dashed curves) and exhibit large individual differences reading ordered words (solid curves). Observer TDB's ordered words curve is about a factor of 2 to the right of the other two observers. This difference in ordered-words reading rate is not unique to our results. Previous studies also exhibit much more individual difference among reading rates for ordered than for unordered words, as we will now discuss.

### Discussion

It is well known that sentence context contributes to the normal foveal reading rate (Chung et al., 1998; Fine & Peli, 1996; Fine et al., 1997, 1999; Latham & Whitaker, 1996a; Morris, 1994) and we replicate previous findings of context gain in the periphery (Fine, 2001).

The text informs the reader through word content (the letters) and word order (the sentence). Readers use both sources of information. For any task for which multiple cues are available, the optimal combination weighs the various cues in accord with their signal-to-noise ratio for the given task (Clarke & Yuille, 1990). Restricting access to word content by placing words in the periphery increases context gain from 1.5 to 3 or more (Fig. D1), indicating increased reliance on word order. This is consistent with the finding that slower readers with poor decoding skills (i.e., access to word content), rely more on sentence context than do fast readers (West & Stanovich, 1978).

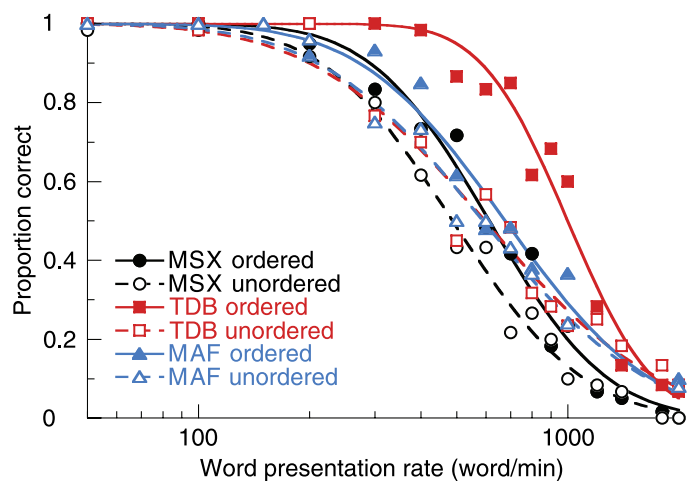


Figure D2. Foveal reading accuracy for ordered and unordered words as a function of presentation rate. The results for unordered words (dashed) show much less difference across observers than do the results for ordered words (solid).

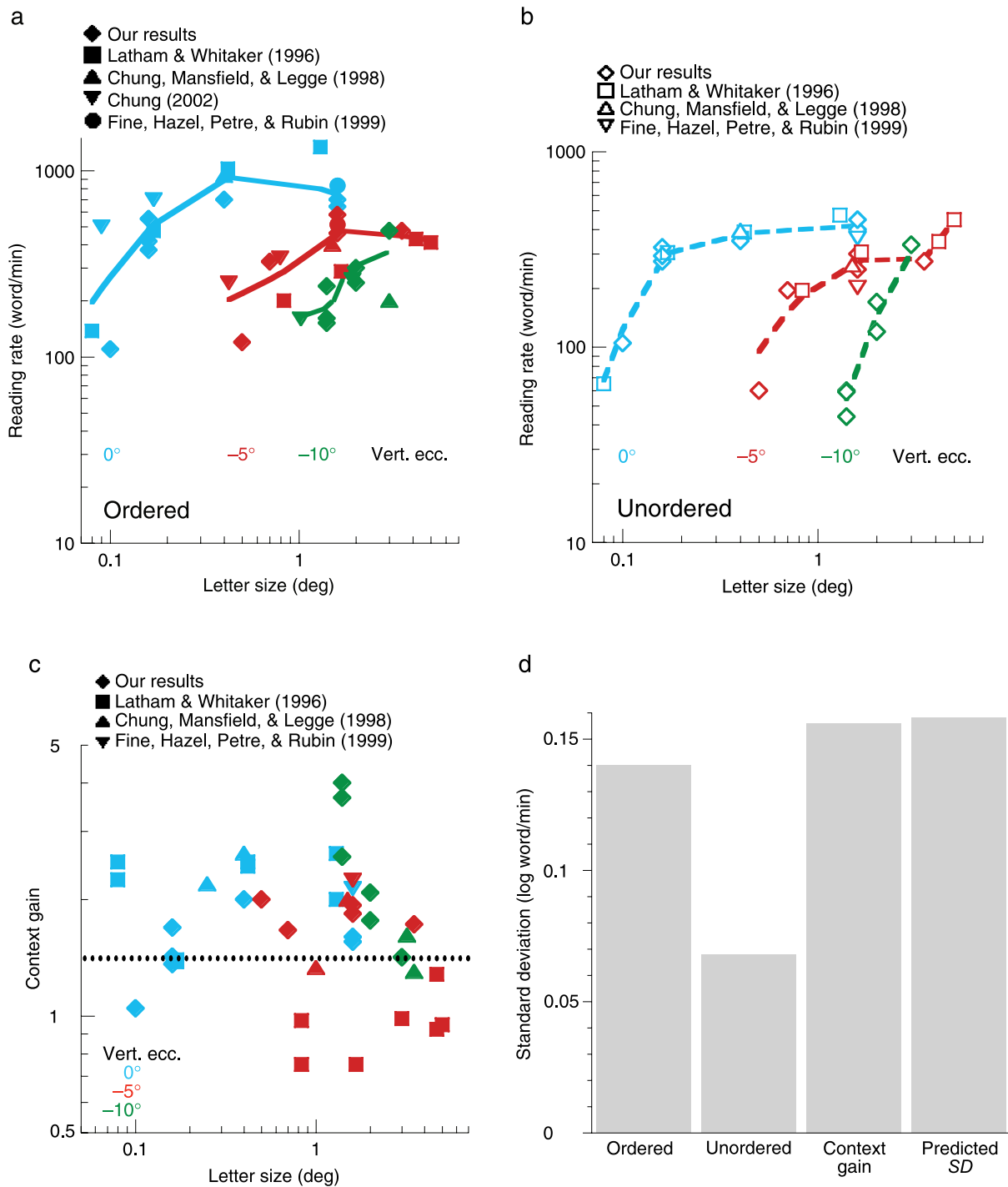


Figure D3. Reading rate and context gain across studies. (a) Reading rate for ordered words as a function of letter size at 0°, -5°, and -10° vertical eccentricity (blue, red, and green, respectively). (b) Reading rate for unordered words as a function of letter size for 0°, -5°, and -10° vertical eccentricity. At every eccentricity, the rate is much less variable for unordered than for ordered words. Chung (2002) did not measure reading rate for unordered words. (c) Context gain as a function of letter size. *Context gain* is the ratio of reading rates for ordered and unordered words. Ordered reading rate is highly variable, so context gain is too. (d) The standard deviation of the log reading rate residuals in panels a and b. (The residual is the difference in log reading rate between the data point and the fitted curve.) The standard deviation for ordered text (0.14) is twice that for unordered text (0.07). The standard deviation of the context gain is even higher (0.16) and is well predicted (rightmost bar) by supposing that the ordered and unordered variations are independent. (Let  $R_o$  and  $R_u$  be log reading rate for ordered and unordered words. Let  $R_{o/u} = R_o - R_u$  be log context gain. If the ordered and unordered variations are independent then the sum of their variances will equal the variance of the context gain. The bar heights, left to right, are  $\sigma_o$ ,  $\sigma_u$ ,  $\sigma_{o/u}$ , and  $\sqrt{\sigma_o^2 + \sigma_u^2}$ .)



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