Crowding limits reading

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Summary. Peripheral reading is slow, even in RSVP, which minimizes the need for eye movements. This affects everyone who reads with central field loss, yet is still unexplained. Legge et al. suggest that reading rate is proportional to visual span, which shrinks with increasing distance from fixation. Both centrally and peripherally, we show that visual span and reading rate are limited by crowding.

When a word is presented in the periphery, the letters crowd each other unless they are far apart (Fig. 1). Crowding also affects the more-peripheral letters of a centrally-presented word. Bouma measured the *critical spacing* to relieve crowding and found that it is proportional to eccentricity.

In ordinary reading, observers make 4 fixations per second, and this rate is quite fixed. Variations in reading rate reflect variations in the number of letters acquired per fixation. Similarly, Legge et al. propose that RSVP reading rate is proportional to the visual span, which they define as the number of characters of text that fit in the window of visibility. For each letter size, they measure the visual span by asking observers to identify a triplet of letters as a function of position in the visual field (Fig. 2). They find that visual span shrinks with eccentricity, but never explain why.

We took the triplet paradigm and tested it for crowding (Fig. 3). The triplet consists of a central target letter and two flanker letters. For 3 locations, we measured the required spacing for identification of the central letter target when two flankers are placed (symmetrically) at various angles relative to it. The ellipses trace out the critical spacing. The width of the ellipse is the width of the triplet, when it is horizontal. The ellipses grow in proportion to eccentricity and point toward the fovea. Furthermore, the ellipses are independent of letter size.

So, what limits the visual span? Acuity? Lateral masking? Crowding? The size independence proves that it's not acuity. The eccentricity dependence proves that it's not lateral masking. It's crowding!

Let's use what we know about crowding to predict reading rate. Critical spacing is proportional to eccentricity. We call the proportional constant b, for Bouma. Taking into account the letter spacing and eccentricity, a bit of trigonometry shows that the visual span (within which all letters are more-than-critically spaced, to escape crowding) for horizontal text is:

$$l = 2\sqrt{\frac{1}{b^2} - \left(\frac{e_V}{s}\right)^2}, \qquad (1)$$

where the span l is in letters, s is letter spacing (deg) and e_V is the vertical eccentricity (deg). The span l is zero when the spacing is less than critical, $s < be_V$. Legge posited that reading rate r is proportional to visual span l,

$$r = \rho l \qquad (2)$$

with proportionality constant ρ. We fit Eq. 2 to the Chung et al. measurements of reading rate, at several vertical eccentricities, as a function of letter size (Fig. 4). The model fits. The Bouma critical-spacing factor b is 0.09. Legge's reading rate factor ρ depends on eccentricity (Fig. 5). The good fit to the Chung et al. data shows that in all conditions tested (all spacings and sizes, central and peripheral), crowding limits reading.

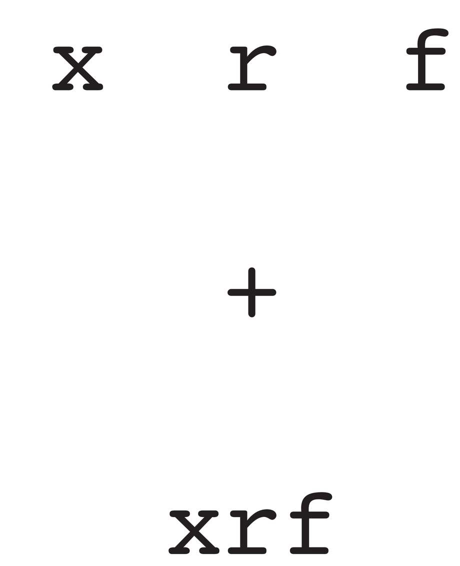

Figure 1. Crowding. Fixate on the cross. It is much easier to identify the isolated letter (above) than the crowded letter (below).

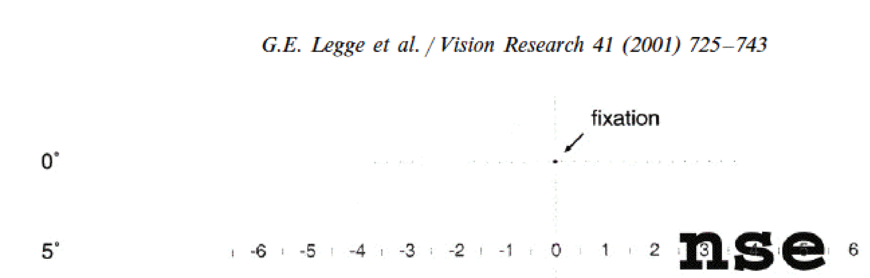

Figure 2. "Visual span" as defined by Legge et al. 2001. Observers are asked to identify letters in a triplet, as a function of letter size and position in the visual field. *Visual span* is the number of letters in the line of text that fit in the window of visibility for that letter size.

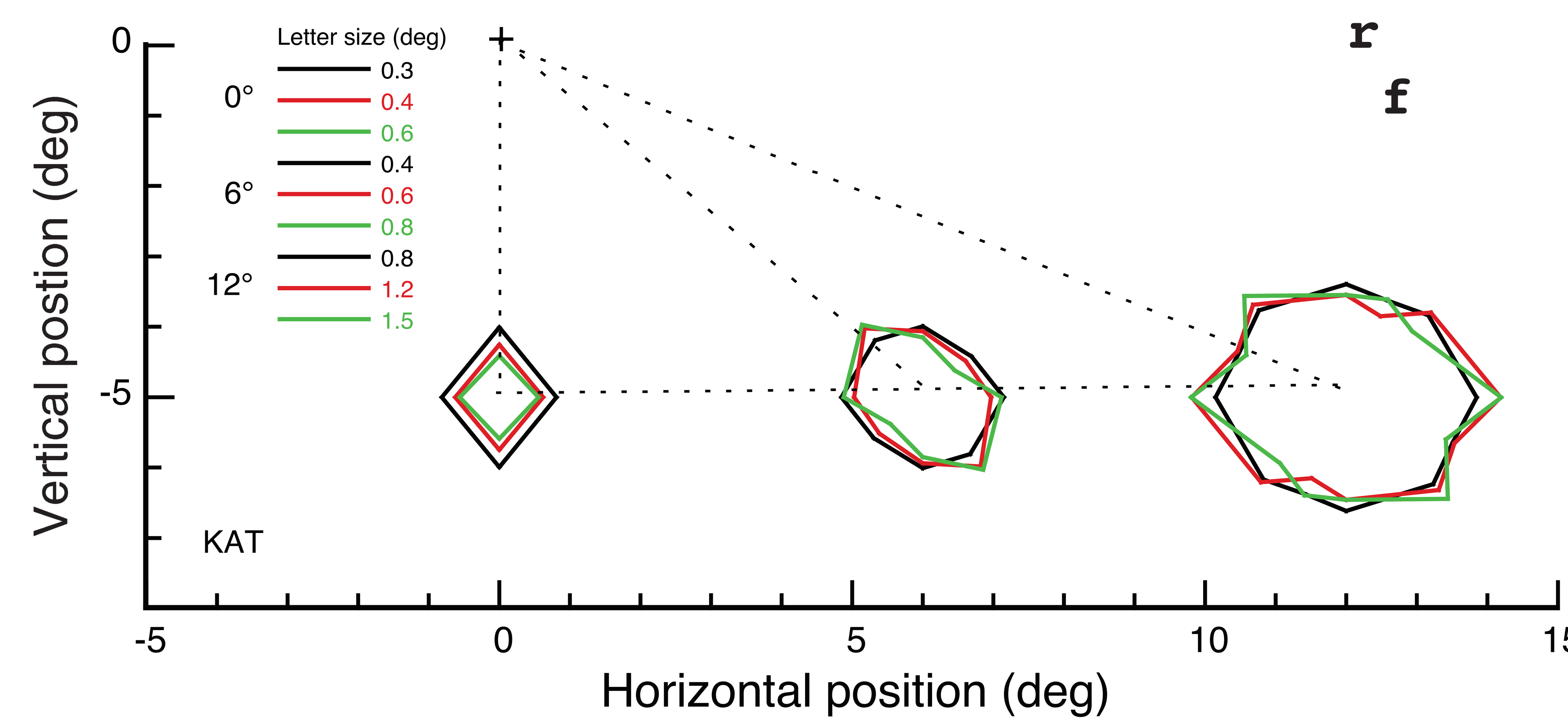

Figure 3. Critical spacing. This plots position in the visual field, relative to the fixation point (black cross). The colored contour lines trace out the letter-to-letter spacing required to achieve 50%-correct identification of a target letter between two flankers. Black, red, and green curves represent different letter sizes at each eccentricity. The critical spacing is proportional to radial eccentricity and independent of letter size.

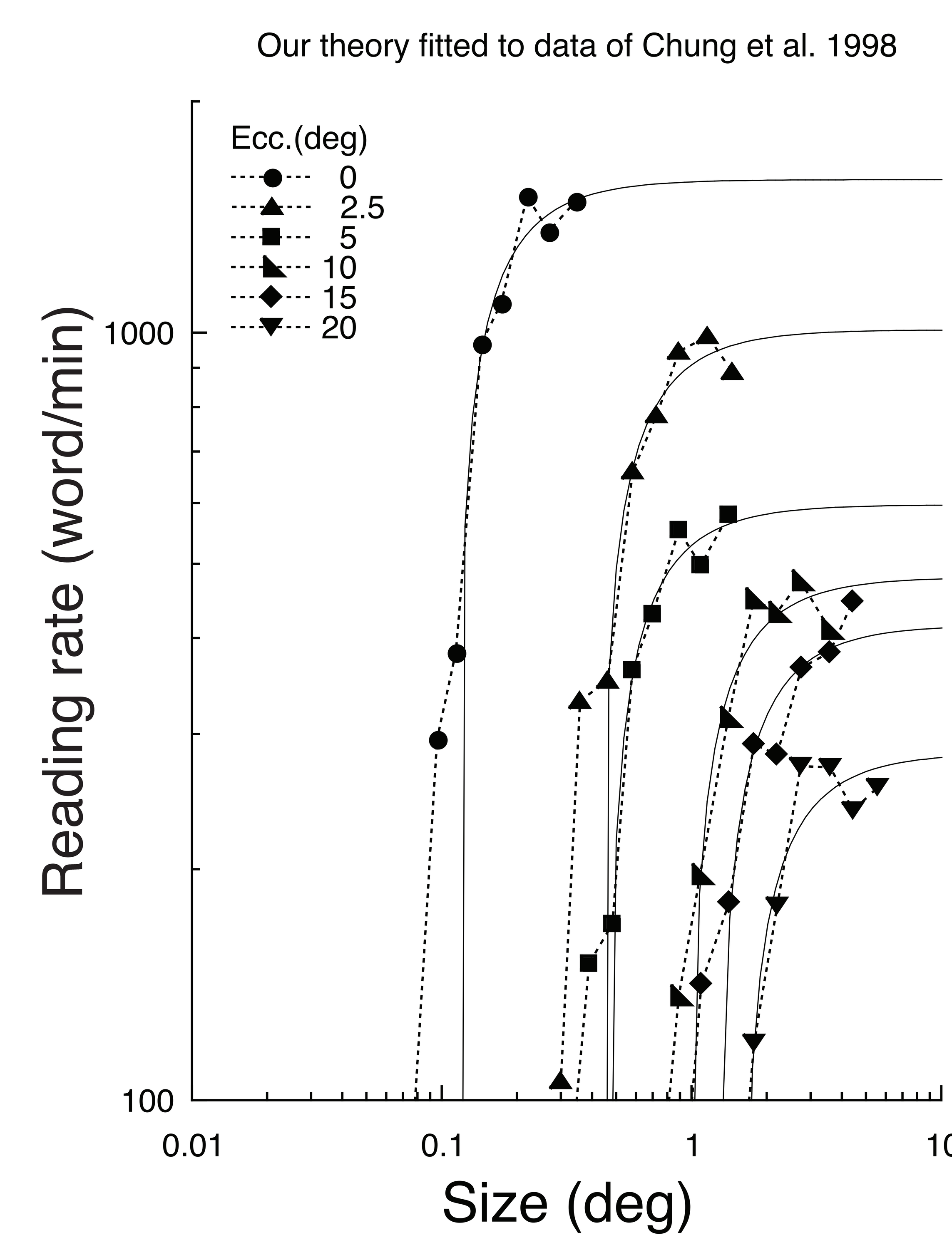

Figure 4. Reading rate. Our model has only two degrees of freedom, b and ρ, yet fits the data well. The reading rate curves have the classic shape: a steep rise to a flat plateau. The cliff edge is the "critical print size," beyond which reading rate is independent of letter size. In these data, letter spacing equals size. The curves are vertical at the critical spacing. Thus critical print size and critical spacing correspond.

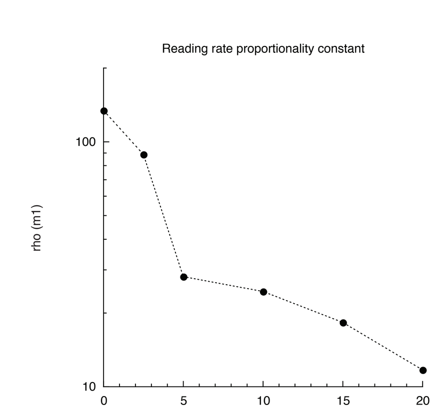

Figure 5. The proportionality constant ρ (between reading rate and visual span) as a function of eccentricity.

Conclusion. **The visual span is determined by crowding: not acuity, not ordinary masking. Crowding is characterized by one number: Bouma's proportion *b*. Assuming that reading rate is proportional to visual span predicts reading rate over the entire tested range of spacings, sizes, and eccentricities.**

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