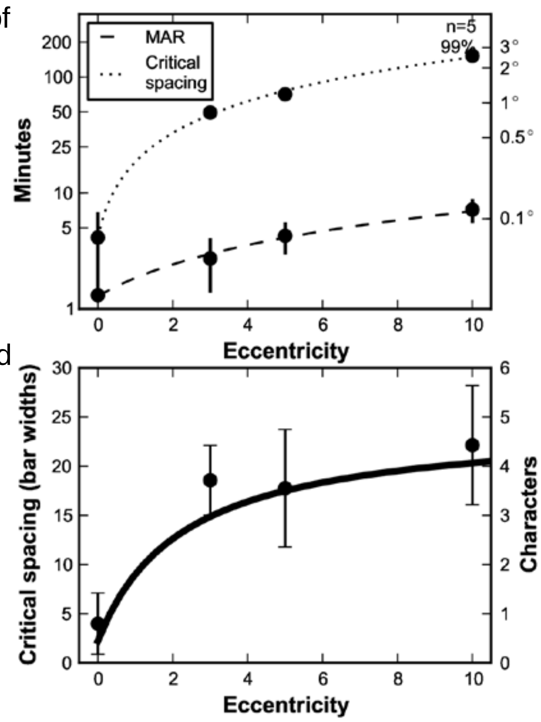
Appendix 1. Flom vs. Bouma, quantifying the critical spacing of crowding

The ‘critical spacing’ of crowding (maximum distance over which flankers interfere with recognition of a target) was first quantified in the 1960s by Flom, et al. (1963) in the fovea with small high contrast Landolt Cs (at resolution thresholds: ~5 min letters for normal observers). A crucial result was that the maximum spatial extent of the foveal zone of interference scaled with the MAR of the subjects, including amblyopic eyes having a much larger MAR than normal eyes. Others have reproduced their finding that foveal crowding extends no further than an edge-to-edge spacing equal to 1x the size of the target (or 5x the gap/bar width). Levi, et al. (2002) have shown this size dependence with a wide range of foveal target sizes (4' to greater than 100'), measured as the distance at which contrast thresholds increase instead of percent correct or MAR.

Peripheral studies, on the other hand, typically measure the spatial extent of crowding in terms of the *angular* separation between adjacent optotypes, beginning with Bouma (1970), who estimated crowding to extend approximately 0.5 times the eccentricity (in degrees). The suitability of this method is bolstered by the finding that the spatial extent of *peripheral* crowding (unlike foveal) is independent of the target size over a large range (Pelli 2004; Tripathy & Cavanagh 2002; Levi, et al. 2002).

Information about the crowding zone in terms of bar widths at the acuity limit is important in order to identify limitations of peripheral acuity measurements using letter charts. Researchers who have evaluated peripheral crowding in terms of bar widths have found that peripheral crowding extends farther than 5x (Jacobs 1979), the spacing of most commercially available charts, and potentially much farther.



These two ways to specify the critical spacing are not mutually exclusive, and extending Flom's analysis into the periphery is possible. MAR for isolated letters increases linearly with eccentricity (known since Weymouth, 1958), and the extent of crowding also increases linearly with eccentricity, following Bouma's 'law' (1970). The Bouma fraction relating angular separation to eccentricity depends on the task (Pelli 2004), typically taking on values from 0.15 to 0.5 (in degrees). The slope of isolated letter MAR vs. eccentricity can vary from 0.15 to 0.8 (measured in minutes; cf. Jacobs 1979).

Fundamentally, the nominal edge to edge critical spacing is found by dividing the angular critical spacing (in min) by the isolated MAR (in min) at each eccentricity, yielding the number of bar widths for the crowding zone at the acuity limit. The figure illustrates this procedure on the data from our 5 subjects. The top panel shows the average MAR and the average angular critical spacing (determined using the two line fit described in the main text). The bottom panel shows the curve that results from dividing the two fitted curves. The points and error bars show the empirical nominal critical spacings determined by averaging the nominal critical spacing of the 5 subjects at each eccentricity.

The parametric line fit for isolated letter MAR is (0.57*E+1.28 min) and for critical spacing is (14.4*E+4.13 min). The corresponding E_2 (eccentricity where the foveal value doubles) measures are thus: E_2(MAR)=2.27, E_2(crit. spac.)=0.29, which are comparable with the literature (cf. Latham&Whitaker 1996, Strasburger 2012). The Bouma fraction for crowding in these data is a typical 0.2-0.3 x Ecc. in deg (cf. Pelli 2004).

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