

## Appendix 2. Two line fit justification, and prediction of crowded acuity

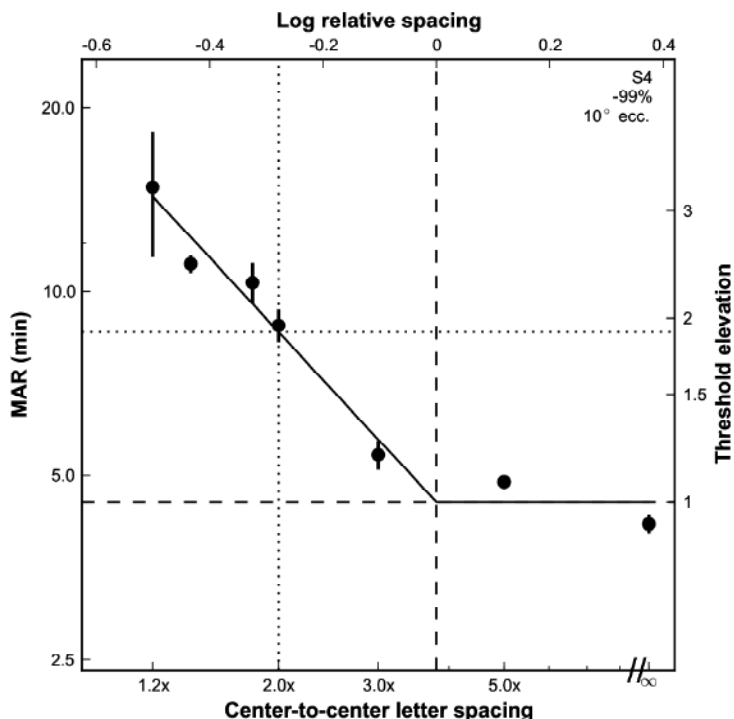
This document summarizes (and motivates) the two line fit of acuity versus center-to-center nominal character spacing used throughout the study. The fit originates from Denis Pelli, and has been used by Song, Levi, Pelli (to be submitted to *J. Vis.*), Pelli (2011), Song (2009), and Chung (2011), to model crowded acuity in the periphery and fovea of normal observers, amblyopes, and subjects with AMD.

The fit (shown in the first figure, below) has two main features. First, a horizontal portion outside the critical spacing, where flankers do not affect recognition of the target, and thus the threshold is a constant function, limited only by isolated acuity for the given condition. Second, a portion where the nearby flankers “crowd” the target, causing acuity to worsen. The crowded region can be represented by a line with a slope of -1. Here threshold elevation is inversely proportional to letter spacing: smaller spacings yield greater threshold elevation. The fit for our data is good, especially in the periphery, where the average  $R^2$  is 0.85. Furthermore, there is a clear intuitive motivation for the relationship, which is described below.

The success of this model in fitting the data allows prediction of crowded acuity. Since the log spatial extent and the log magnitude of crowding-limited acuity (the threshold elevation) are inversely proportional, knowledge of either can be used to predict performance on any part of the curve. For example, consider the dotted and dashed lines shown in the graph. The dashed lines indicates the critical spacing and MAR for this condition, at 10 degrees eccentricity. The vertical line indicates the critical center-to-center spacing (in character widths), here approximately 4x, or an edge-to-edge spacing just under 15 bar widths. The upper axis shows how each letter spacing relates to this critical spacing (in log units). The horizontal dashed line shows the isolated MAR. The dotted lines demonstrate the consequence of using a standard letter chart spacing (one with a 1 letter (5 bar widths) edge-to-edge separation) under these conditions. First, the vertical line shows that at this center-to-center spacing (2x letter width), the relative spacing is 0.28 log units ( $\log_{10}4 - \log_{10}2$ ) closer than the critical spacing. Due to the inverse proportionality relationship, the crowded MAR will be  $10^{0.28}$  ( $\approx 1.9$ ) times worse than the isolated acuity. This is approximately  $\sim 0.3$  log units, or 3 lines worse.

In fact, since we found the nominal critical spacing to be roughly invariant over the eccentricities we tested (3-10°, see main text or Appendix A), the elevations of MAR across subjects were all approximately 2 times for this letter spacing throughout the periphery. This can be compared to the results of Jacobs (1979), who found a threshold elevation of approximately 1.5x for his 5 bar width condition from 2-10° eccentricity, which is comparable to the example condition: his flanking bars correspond to the innermost bars of Tumbling Es at 2x center-to-center, though the differing experimental paradigms prevent exact comparison.

The success of the negative one slope has a clear intuitive meaning. The argument depends fundamentally on the observation that the angular size of the “crowding zone” (the area over which



flankers interfere with the target) is dependent solely on the eccentricity, being invariant to the size of the characters and other stimulus manipulations. The dependence on eccentricity has strong support dating back to Bouma (1970), and the independence on stimulus conditions (including size) also has strong evidence, especially in the periphery (Pelli 2004, Levi 2002, Tripathy & Cavanagh 2002). In the figure below, the crowding zone is represented by the dashed ellipses. The elliptical shape follows Toet & Levi (1992). The basic idea is that when flankers are within the same ellipse as the target, features from the flankers will be 'integrated' with the target and impair its detection. Each row represents a different letter size. The variable of interest is the spacing that will cause the two flanking characters to fall outside of the crowding zone. Put another way, at what letter spacing (which depends on the character size) is the critical spacing for crowding achieved? The schematic figure depicts the exact letter spacing at which the flanking optotypes are at the critical spacing for each letter size. Note the center-to-center separation (in letters) and the letter size (in arbitrary units) indicated beside each row. Because of the trade-off between size and spacing, the critical separation and the letter size have a constant product of 90, which is the horizontal radius of the crowding zone oval in this cartoon. So, larger letters permit a smaller spacing whereby flankers are beyond the critical spacing of interference, while smaller letters need to be farther away (in terms of multiples of letters). This exact inverse proportionality motivates the use of the -1 slope to fit the data, which (as stated), also has empirical support from data. The efficacy of this construction dictates the use of center-to-center spacing instead of edge-to-edge spacing, although conversion after fitting is possible, as was performed in the main paper.

letter size = 60 units  
center-to-center separation  
= 1.5x letter size



letter size = 30 units  
center-to-center separation  
= 3x letter size



letter size = 15 units  
center-to-center separation  
= 6x letter size



## REFERENCES

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