Appendix A. Modeling areal summation for DPR, consequences from the Ferry–Porter law

A particularly explicit model of critical flicker fusion frequency (CFF), based on the Ferry–Porter law, is given by Tyler and Hamer (1990, Fig. 6). Since we will base our account of areal summation on that model, we first need to reformulate it for our needs.

The Ferry–Porter law describes the dependency of CFF on stimulus luminance,

$$f = k(\log L - \log L_0), \tag{1}$$

where f is the CFF in Hz, k is a parameter that is constant with stimulus luminance but depends on other stimulus characteristics, and L and L_0 are luminance and luminance threshold, respectively. The Ferry–Porter law plays only a limited role here since stimulus luminance is constant (at 215 cd/m^2) in our experimental conditions. However, threshold luminance L_0 (at which $f = 0$) depends on stimulus diameter and on eccentricity, by which areal summation is introduced into Eq. (1). By interpolation between the two respective L_0 values provided at the foveola [Tyler and Hamer (1990, Fig. 6), log $L_0 = -0.64$ at $d_0 = 0.5°$ and log $L_0 = 0.86$ at $d_0 = 0.05°$], we obtain in the fovea

$$\log L_0 = -1.5 \log d_0 - 1.09 \tag{2}$$

(with log denoting the decadic logarithm). The slope of areal summation (−1.5) in the equation is half way between Riccò's (−2) and Piper's (−1) law.

Tyler and Hamer also measure at 35° eccentricity and use scaled stimuli of the size 0.5° and 5.7°, to compensate for the peripherally smaller cortical projection area. Interestingly, as seen in their graph, the 35° Ferry–Porter functions with these diameters intersect at the same L_0 values (log 0.64 and 0.86) as the foveal functions. Analogous to Eq. (2), threshold luminance L_0 can thus also be specified using these values in the visual periphery ($L_0 = -0.64$ at 5.7° and $L_0 = 0.86$ at 0.5°, which results in $\log L_0 = -1.42 \log d_{35°} + 0.43$). Tyler and Hamer's Fig. 5 provides two additional estimates for the area dependency at 35° eccentricity. From the x axis intercepts there we can derive by linear regression

$$\log L_0 = -1.27 \log \mathrm{d}_{35°} + 0.40. \tag{3}$$

Note that the slope of areal summation and the intercept value are different from those in the fovea. There is less summation and threshold luminance is shifted to higher values. The two equations can be combined by interpolation to give

$$\log L_0 = (-1.5 + 0.00657E) \log d_E - 1.09 + 0.0426E \tag{4}$$

or, approximately

$$\log L_0 = -1.39 \log d_E - 1.09 + 0.0426E, \tag{4a}$$

where d_E is the diameter of the stimulus presented at eccentricity E.

The slope coefficient k in the Ferry–Porter law Eq. (1) depends, according to Tyler and Hamer, on eccentricity E but not on stimulus size. From the two slope values provided there ($k = 19$ Hz/decade at $E = 35°$ and $k = 10.5$ Hz/decade at $E = 0°$) we obtain, again by interpolation,

$$k = 0.24E + 10.5 (\mathrm{Hz/decade}). \tag{5}$$

With Eqs. (1), (2), (4a), and (5), the data in Tyler and Hamer (1990, Fig. 6) can thus be summarized by

$$\begin{aligned} f &= f(E, L, d) \\ &= (0.24E + 10.5)(\log L + 1.39 \log d_E - 0.0426E \\ &\quad + 1.09)(\mathrm{Hz}) \end{aligned} \tag{6}$$

where f is the CFF in Hz, E is the eccentricity in degrees, L is the retinal illuminance in Troland, and d_E is the stimulus diameter in deg (at eccentricity E). Fig. 8 shows the dependency on log illuminance L_{ill} by Eq. (6), for verification with Tyler and Hamer (1990, Fig. 6).

Up to this point, the calculations were to verify that the interpolation parameters agree with the results of Tyler and Hamer. Now, for an approximate conversion from retinal illuminance L_{ill} (T_{d}) (for which the parameters in Tyler and Hamer are specified) and luminance L, we use $L_{\mathrm{ill}} = L \cdot A$ and assume a mean constant pupillary area A of 13 mm^2 (using Reeves,' 1920 formula with an observer dark-adapted to 1 cd/m^2),

$$\log L_{\mathrm{ill}} = \log L + \log(13). \tag{7}$$

For example, 215 cd/m^2 corresponds to 3.45 log T_{d}.

As a function of luminance L in cd/m^2, Eq. (6) thus becomes

$$\begin{aligned} f &= f(E, L, d) \\ &= (0.24E + 10.5)(\log L + 1.39 \log d_E - 0.0426E \\ &\quad + 2.2)(\mathrm{Hz}) \end{aligned} \tag{8}$$

(noting that log 13 = 1.11). Note that for given eccentricity and luminance, Eq. (8) can be re-written as a function of stimulus diameter

$$f = f(d) = k_1 \log d + k_2 (\mathrm{Hz}) \tag{9}$$

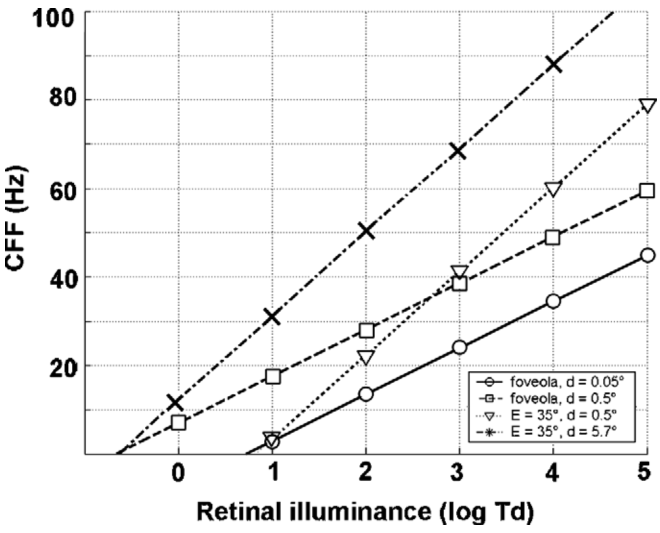

Fig. 8. Dependency of CFF on retinal illuminance. Verification of the modeling equations by comparison with data from Tyler and Hamer (1990, Fig. 6): retinal illuminance is plotted against CFF for different stimulus diameters and positions in the visual field, according to Eq. (6).

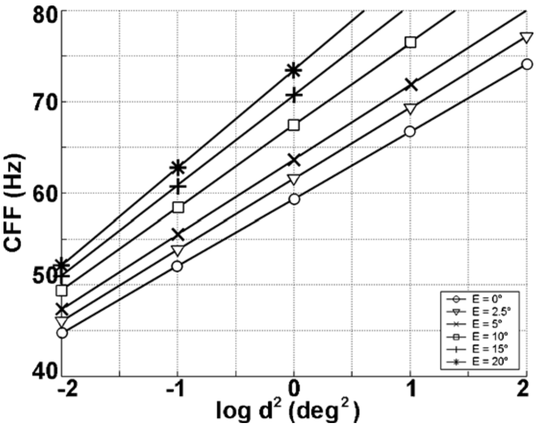

Fig. 9. CFF areal summation functions at different eccentricities, based on Tyler and Hamer's (1990) formulation of the Granit-Harper law, for the stimulus eccentricity values used in our study.

(with $k_1 = 1.39$ k, and $k_2 =$ k (log $L - 0.0426\ E + 2.2$)) (k as in Eq. (5)) for a formal comparison with the Granit-Harper law of areal summation. The law is violated since k, as we have seen above, is not a constant but depends on eccentricity. Fig. 9 shows Eq. (9) for the luminance (and corresponding retinal illuminance) used in our experiment and a number of eccentricities, i.e., the areal summation functions.

In our experiments stimulus size is constant at 1.15° visual angle. The cortical projection area $d_{\text{cortex}} = M \cdot d$ of our stimulus will thus decrease with stimulus eccentricity E by

$$M/M_0 = (1 + E/E_2)^{-1}, \tag{10}$$

where M_0 is the foveal magnification factor and E_2 is the model parameter introduced by Denis Levi. We assume $E_2 = 0.75$, based on anatomical data by Horton and Hoyt (1991). If one would use M-scaled stimuli of diameter $d' = (M^{-1}/M_0^{-1}) \cdot d$ in Eq. (8), CFF would become

$$\begin{aligned} f_{\text{scaled}} = {} & (0.24E + 10.5)(\log L + 1.39 \log(M^{-1}/M_0^{-1})d_0 \\ & - 0.0426E + 2.2)(\text{Hz}) \end{aligned} \tag{11}$$

or

$$\begin{aligned} f_{\text{scaled}} = {} & (0.24E + 10.5)(\log L + 1.39 \log((1 + E/E_2)d_0) \\ & - 0.0426E + 2.2)(\text{Hz}). \end{aligned}$$

The effect of using scaled stimuli is given by (f_{scaled}/f):

$$\begin{aligned} f_{\text{scaled}}/f = {} & (\log L + 1.39 \log((1 + E/E_2)d_0) \\ & - 0.0426E + 2.2)/(\log L + 1.39 \log d_0 \\ & - 0.0426E + 2.2). \end{aligned} \tag{13}$$

Now let $\tau = \tau(E)$ denote the empirically found value of double-pulse resolution at eccentricity E. We assume τ as inversely related to f, and thus model

$$\tau_{\text{scaled}} = \tau/(f_{\text{scaled}}/f). \tag{14}$$

At the fovea, $E = 0$ and [from Eqs. (13) and (14)] τ_{scaled} is equal to τ .

Fig. 5 in the main text shows this scaled function from Eq. (14).

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