What internal noise source limits peripheral vision?

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INTRODUCTION & METHOD.
Measuring equivalent input noise (defined below) is a good way to assess the sensitivity of a sensor. Originally developed for radio, it quickly extended to many electronic sensors. Albert Rose (1948) at RCA extended it to video cameras and the eye.

Here we extend the foveal measurements of Pelli & Raghavan (2016) to the periphery. We measure the equivalent input noise of human observers and compare it with that of models for three known sources of visual noise. The noises are independent, so we expect the human noise to be the sum of all sources.

Under our conditions, measurements of threshold signal energy as a function of the added white noise level always follow the linear relationship displayed in Fig. 1,

\[ E \propto N + N_{eq} \]

where \( E \) is the threshold energy, \( N \) is added display noise, and \( N_{eq} \) is the linear intercept, our operational definition of equivalent input noise. That linear input-output relationship (the additive effects of noise on threshold energy) is all we need to apply the equivalent-noise technique. The psychophysically measured equivalent input noise is predicted to be the sum of the equivalent input noises of the various sources,

\[ N_{eq} = N_{\text{photon}} + N_{\text{ganglion}} + N_{\text{cortical}} \]

Eq. 2 is our model, the sum of three noises. They are plotted in Fig. 3. We model the noise sources as:

\[ N_{eq} = a/L + b/D + kA \]

THREE MODELS

PHOTON (blue in Fig. 3). Photon noise results from independent photon transductions in the retina, with Poisson statistics. Calculation and simulation show that it has an equivalent input noise equal to the reciprocal of the flux of transduced photons. It is proportionally luminal, independent of letter size, and therefore approximated as independent of eccentricity. For each observer, parameter \( a \) is set by fitting Eq. 3 to data in Fig. 4.

\[ N_{\text{photon}} = a/L \]

GANGLION (yellow in Fig. 3). Retinal ganglion cells transmit the visual signal to the brain through the optic nerve, consisting of one million axons. Retinal ganglion cell spikes are approximately Poisson and their noise is independent of eccentricity (Croner and Kaplan, 1995) and luminance. The equivalent input noise of the ensemble is the reciprocal of the product of spike flux (spikes deg\(^{-2}\) s\(^{-1}\)) and the square of retinal contrast gain. (This relationship was determined analytically and confirmed by simulation.)

\[ N_{\text{ganglion}} = b/D \]

where \( D \) is ganglion cell density (deg\(^{-2}\)) from Watson (2014). Ganglion cell density is higher in temporal than nasal visual field, so \( N_{\text{ganglion}} \) is lower in temporal (dashed line) than in nasal field (solid line). For each observer, parameter \( b \) is set to fit data in Fig. 4.

CORTICAL (magenta in Fig. 3). We use the model proposed by Pelli & Raghavan (2016) based on their extensive foveal measurements of equivalent input noise. This model assumes scale-invariant processing, devoting the same number of independent cortical spikes to identify a letter, regardless of its luminance, size, and eccentricity.

\[ N_{\text{cortical}} = kA \]

where \( k \) is a constant (deg\(^{-2}\)), the square of letter size. For each observer, parameter \( k \) is set to fit data in Fig. 4.

CONCLUSION. The sum of the three noise sources accounts for the human noise. In this account, peripheral sensitivity is limited primarily by ganglion cell noise, assumed to be the product of density, firing rate, and squared contrast gain of retinal ganglion cells. The cortical noise (in identifying a letter) is independent of eccentricity, despite the huge drop in cortical magnification with eccentricity.

REFERENCES


