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 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.

NOTE. Human vision is a complex biological system and has nonlinearities lurking in every corner. Perceptual decisions such as object recognition are necessarily nonlinear. However, applicability of the equivalent noise technique does not require that the individual components behave linearly. The equivalent noise technique models the input-output behavior of the system as a whole.

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,

$$E \propto N + N_{eq} \qquad (1)$$

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,

$$N_{eq} = N_{photon} + N_{ganglion} + N_{cortical} \qquad (2)$$

Eq. 2 is our model, the sum of three noises. We model the noise sources as:

$$N_{eq} = a/L + b/D + kA \qquad (3)$$

where L is luminance (cd/m^2), D is retinal ganglion cell density (1/deg^2), A is signal area (deg^2), and a, b, and k are fitted constants, determined by fitting Eq. 3 to the measured N_{eq} in Fig. 5, separately for each observer.

Fig. 2 shows threshold contrast (average of 2 observers) for identifying a letter with and without a noise background (rms contrast 0.16). We do this for letter sizes 1 to 16 deg at eccentricities 0 to 60 deg, omitting points beyond the acuity limit. We can express these thresholds as threshold energy E in noise and threshold energy E_0 without noise. Plugging both into Eq. 1 and solving for N_{eq} gives us a formula for equivalent input noise:

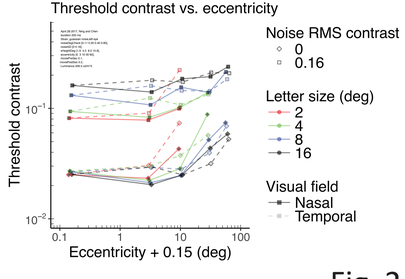

Fig. 2

$$N_{eq} = N\,E_0/(E-E_0), \qquad (4)$$

where N is the power spectral density (deg^2 s) of the noise. This is plotted in Fig. 5, for 2 observers. We also developed models of three sources of visual noise: photon, ganglion, and cortical.

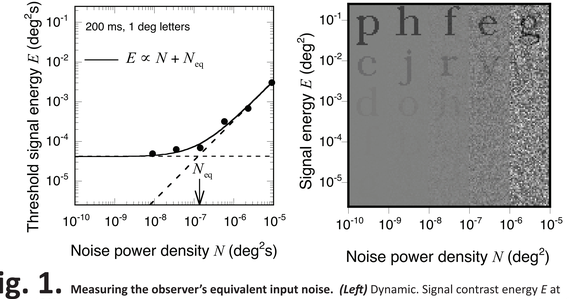

Fig. 1. **Measuring the observer's equivalent input noise.** ***(Left)*** Dynamic. Signal contrast energy E at threshold (64% correct) for identifying letters on a background of dynamic visual noise is plotted as a function of the display-noise power spectral density N. The good fit provided by Eq. 1 shows that threshold signal energy depends linearly on display noise N, where the *equivalent input noise* N_{eq} is a fitted constant. The curve asymptotically approaches the two dashed lines (slopes 0 and 1), which intersect at N_{eq}. ***(Right)*** Static. You can use this letters-in-noise chart to test your own vision at a distance of 40 cm. You will find that the faintest identifiable letters trace out a curve similar to that plotted in *a*. The noise level at which the curve turns up is your static equivalent input noise for letters of this size. (From Pelli & Raghavan, 2016)

THREE MODELS

PHOTON (Fig. 3, red). 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 proportional to luminance, independent of letter size, and here approximated as independent of eccentricity (red lines in Fig. 3). For each observer, parameter a is set by fitting Eq. 3 to data in Fig. 5.

$$N_{photon} = a/L \qquad (5)$$

GANGLION (Fig. 3, blue). 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.)

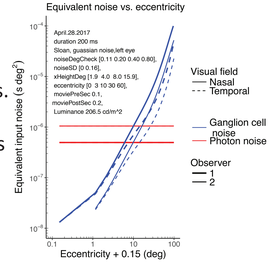

Fig. 3

$$N_{ganglion} = b/D \qquad (6)$$

where D is ganglion cell density (deg^{-2}) from Watson (2014). Ganglion cell density is higher in temporal than nasal visual field, so $N_{ganglion}$ is lower in temporal (dashed line) than in nasal field (solid line). For each observer, parameter b set to fit data in Fig. 5.

CORTICAL (Fig. 4). 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 identifying a letter, regardless of its luminance, size, and eccentricity.

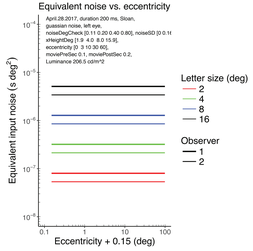

Fig. 4

$$N_{cortical} = k\,A \qquad (7)$$

where A is letter area (deg^2), the square of letter size. For each observer, parameter k set to fit data in Fig. 5.

OBSERVER (Fig. 5). We fit Eq. 3 to the human equivalent noise measurements in nasal and temporal visual field for two observers. The fit has only three degrees of freedom: *a, b, k*.

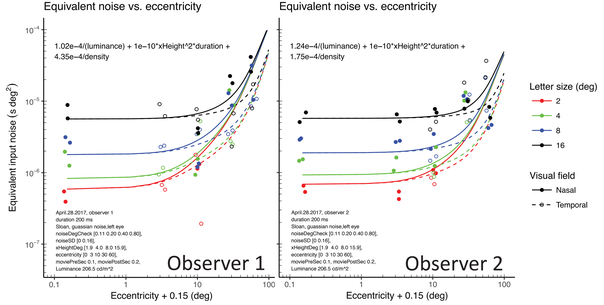

Fig. 5. Fit Eq. 3 to human data.

CONCLUSION. The sum of the three noise sources accounts for the human noise. In this account, peripheral sensitivity is limited primarily by 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.

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