Efficiency of Human Visual Signal Discrimination

Abstract. *We have measured the overall statistical efficiency of human subjects discriminating the amplitude of visual pattern signals added to noisy backgrounds. By changing the noise amplitude, the amount of intrinsic noise can be estimated and allowed for. For a target containing a few cycles of a spatial sinusoid of about 5 cycles per degree, the overall statistical efficiency is as high as 0.7 ± 0.07, and after correction for intrinsic noise, efficiency reaches 0.83 ± 0.15. Such a high figure leaves little room for residual inefficiencies in the neural mechanisms that handle these patterns.*

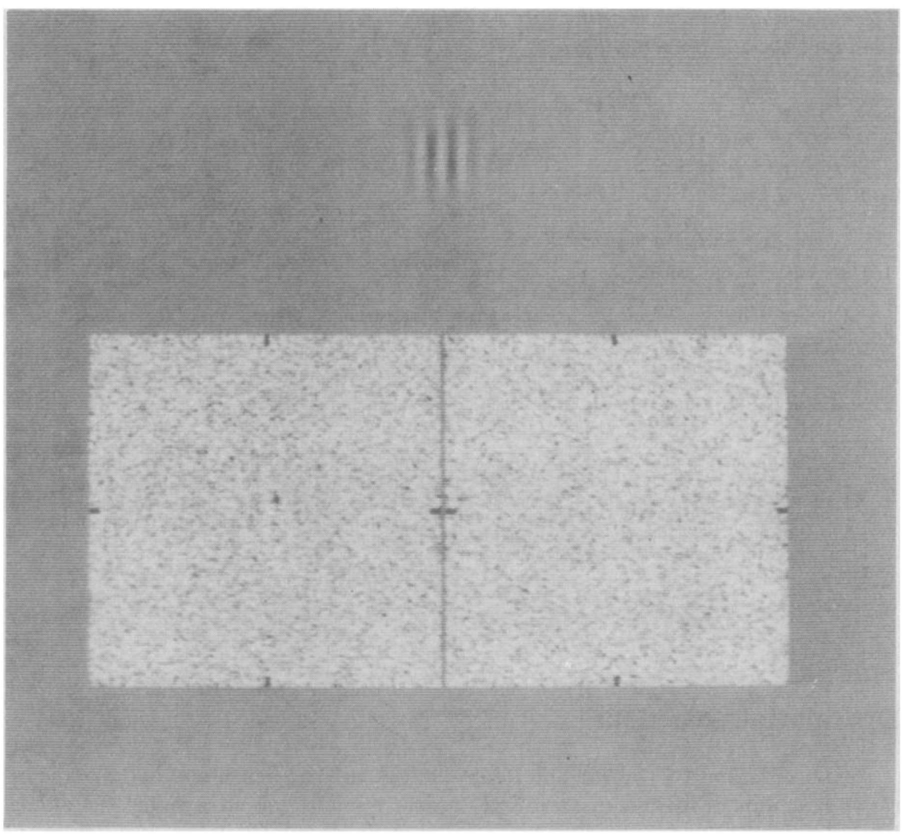
We have measured the ability of human subjects to perform tasks such as that illustrated in Fig. 1. Signals were embedded in the centers of the two squares of image noise, and the subject was asked to indicate which side held the signal of greater amplitude. Our aim was to measure the overall statistical efficiency with which such a task can be performed, and thereby to define levels of performance which any acceptable model of visual processes must at least equal.

Preliminary experiments confirmed previous results (*1*) by showing that suprathreshold discriminations were more efficient than simple detection. Hence, we selected the amplitude discrimination task, for the higher the level of performance achieved, the more stringent is the test applied to a hypothetical model. Our choice of target patterns was guided by current models of early visual processing (*2*).

In most conventional experiments, the human observer is asked to detect or discriminate between signals without added noise. We have added known amounts of static visual noise to the image in order to introduce a source of variability to the signal detection task. An ideal detector (*3*), by definition, does not increase this variability. One can calculate the probability of correct response and the detectability index, d_I', for the ideal detector (*4*). A human observer given the same task will have a lower probability of correct response and hence a lower d'. We define the human observer's efficiency as the square of the ratio of d' values (*5*). This is analogous to comparing real engine performance with that of an ideal engine performing at the limit determined by the second law of thermodynamics.

We determined the amplitude discrimination efficiency of human observers for a number of simple luminance signals, including a Gaussian pulse, sinusoidal pulse bursts with Gaussian envelopes, and two cycles of a sine wave (*6*). The signals were added to spatially uncorrelated ("white") noise and displayed on a cathode ray tube through the use of a Ramtek image display system (*7*). We performed a computer simulation with a realization of the ideal detector. Results agreed with theory within the limits of statistical sampling error.

Averaged results for two observers with four different targets and four noise levels are presented in Fig. 2, together with lines showing the results to be ex-



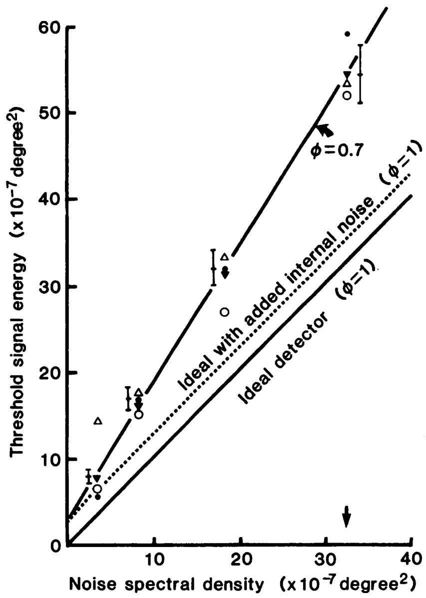


Fig. 1 (left). A sample display with a 9.2 cycle/deg Gaussian modulated sinusoidal signal (when viewed from 86 cm) shown in the upper center. One noise image contains the signal with the same amplitude (E/N = 7.5) and the other contains a version at a lower amplitude (E/N = 5.0). The image noise levels are the highest used in the experiments. The observer's task was to select the noise image containing the higher amplitude signal. An ideal detector would respond correctly 96 percent of trials. Human observers averaged 91 percent correct, and the observer efficiency was 60 percent. Each noise image consisted of 128 by 128 pixels with 256 gray levels. Mean luminance was 154 cd/m^2 and there was no limit on display time. Fig. 2 (right). Mean threshold signal energy (defined for d' = 1) plotted as a function of noise spectral density based on 720 trials per observer per datum, and averaged for two observers. Representative standard errors are indicated. The ideal detector lines are explained in the text, and line ϕ = 0.7 is included for reference. The data for the aperiodic Gaussian signal (f = 0, σ = 0.054 degree) is best fitted by a sampling efficiency of 0.54 ± 0.07. The data for the 4.6 cycle/deg signals (pulse burst with σ = 0.216 degree, and 2 cycles of a sine wave) are best fitted by sampling efficiencies of 0.83 ± 0.15 and 0.64 ± 0.15, respectively. The sampling efficiency for the 9.2 cycle/deg pulse burst (σ = 0.108 degree) was 0.63 ± 0.07. Frequency symbols: ●, 0 cycle/deg; △, 4.6 cycle/deg pulse burst; ▼, 9.2 cycle/deg pulse burst; ○, 4.6 cycle/deg sine wave. The arrow indicates noise with standard deviation per pixel equal to 26 percent of the mean luminance.

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pected on several simple hypotheses. We interpret the results through the use of a model (*8*) that includes a source of variability intrinsic to the observer and a sampling efficiency, ϕ, that is independent of image noise. This sampling efficiency characterizes the performance of the method used by the visual system to sample the image, weight the coefficients appropriately, integrate the result, and utilize a priori information.

One can use the equations of the model (*8*), the definition of d_I', and a threshold signal energy, E_T, defined for an observer d' of unity to obtain the equation $E_T = (N_o + N_e)/\phi$. This equation describes the straight lines plotted in Fig. 2. The ideal detector has $\phi = 1$ and $N_e = 0$, so its performance falls on a line of slope 1. A detector that had $\phi = 1$ and nonzero intrinsic noise would give the dotted line of slope 1 and nonzero intercept. Finally, a detector with intrinsic noise and suboptimal sampling efficiency would give a line of higher slope as is indicated for the observer results. We used the above equation and weighted linear regression of the experimental data to estimate the intrinsic noise spectral density and observer sampling efficiency for each type of target signal.

Our experimental statistical efficiencies were in the range from 0.2 to 0.7 (with standard errors between 0.05 and 0.1) and are model-free estimates. The model-dependent calculations of sampling efficiencies and intrinsic variabilities were highest for a pulse burst of 4.6 cycle/deg. This target was the largest in spatial extent and was located near the peak of contrast sensitivity of the visual system. The other targets had smaller spatial extents, lower intrinsic variance, and lower sampling efficiencies. The sampling efficiencies ranged from 0.54 ± 0.07 to 0.83 ± 0.15.

It is possible that intrinsic observer noise is a function of image noise. For example, $N_e = A + BN_o + CN_o^2 \ldots$ If the coefficients B and C are positive, our estimates of intrinsic noise and sampling efficiency are both too low.

What do these measurements mean? There is not much scope for improvement of the sampling efficiencies we have obtained. It is possible that this very high efficiency occurs because these targets are well matched to processing mechanisms at early levels in the visual pathways. Several models (*2*) hypothesize local Fourier analysis of small regions of image, and this would involve cross-correlation with a few cycles of a spatial sinusoid. Furthermore, "simple" cells in the primary visual cortex of cats and monkeys possess properties that would enable the cells to act as cross-correlators for our "simple" signals (*9*).

There have been models based on sensory cross-correlation of received signals with expected signals. Such a model has been proposed for motion detection and pattern vision (*10*), and for echo location by bats (*11*). Measured human auditory efficiencies up to 0.4 have also been reported for discrimination of damped sinusoidal tones (*12*).

We have presented a method for investigating the absolute performance of the visual system that allows one to separate efficiency loss due to intrinsic observer variability and noise from residual inefficiencies. The results show that the residual inefficiency is very low under certain conditions, suggesting that very efficient processing methods must be used.

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References and Notes

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4. The signals and noise can be described by the ratio, $E/N_o = \int_{-\infty}^{\infty}\int s^2(x,y)dxdy/N_o$, where $s(x,y)$ is the difference between the two displayed signals (differing only in amplitude), E is the signal energy, and N_o is the two-sided spectral density of the noise. For two-alternative forced-choice experiments and complete a priori information, the ideal observer's d_I' is equal to $\sqrt{E/N_o}$. We determined the observer's index, d', from the percentage of correct responses, P, using $d' = 2\,erfi(2P - 1)$, where *erfi* is the inverse error function.
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6. The Gaussian pulse burst of amplitude, A, and frequency, f, is given by $g(x,y) = A \cos(2\pi fx) \exp[-(x^2 + y^2)/2\sigma^2]$, where σ is the standard deviation of the Gaussian envelope (and always equals $1/f$). All signals had height equal to width.
7. The images were generated by computer. The image noise had a Gaussian probability distribution and flat power spectrum.
8. One model will be outlined here. The difference signal $s(x,y)$ has a Fourier transform $S(u,v)$, where u and v are spatial frequencies. An example of a nonideal receiver is one that receives the signal through a predetection filter with frequency response $F(u,v)$, detects the signal through an adaptive filter whose response is $M(u,v)$, and adds intrinsic noise with spectral density $N_iG^2(u,v)$. The detectability index in this case is
$$[d'_G]^2 = I_2^2/(I_3N_o + I_4N_i)$$
with
$$I_2 = \int_{-\infty}^{\infty}\int S(u,v)F(u,v)M(u,v)dudv,$$
$$I_3 = \int_{-\infty}^{\infty}\int F^2(u,v)M^2(u,v)dudv, \text{ and}$$
$$I_4 = \int_{-\infty}^{\infty}\int G^2(u,v)dudv$$
Sampling efficiency, ϕ, is defined as the ratio I_2^2/EI_3, and the effective receiver noise spectral density, N_e, is defined by the ratio N_iI_4/I_3. The statistical efficiency of this suboptimal receiver is
$$F = \left(\frac{d'_G}{d'_I}\right)^2 = \phi\left(\frac{N_o}{N_o + N_e}\right)$$
An energy-detector model is also consistent with our results [D. B. Green and J. A. Swets, *Signal Detection Theory and Psychophysics* (Wiley, New York, 1966), pp. 209–232].
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13. We thank J. Sandrik for his assistance in display calibration, D. Pelli for useful discussion and comments, B. Fowler for assistance in preparing this manuscript, and A. B. Watson for suggesting that we use σ equal to the reciprocal of f. This work was done while A.B. held an FDA visiting scientist award at the Bureau of Radiological Health.

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Hydralazine Reactions

The observations by Dubroff and Reid (*1*) on reactions of hydralazine with ^{3}H-labeled thymidine and ^{3}H-labeled deoxycytidine in aqueous solutions, both in the dark and in the presence of light, need to be criticized. (i) Hydralazine is extensively (85 percent) bound to human plasma proteins (*2*). At the usual dose, the highest free concentration is $10^{-7}M$ to $10^{-6}M$; Dubroff and Reid used $10^{-5}M$ to $10^{-1}M$. (ii) The half-life of hydralazine in man is short (about 1 hour), and thus average plasma levels are even lower (*3*, *4*). (iii) Dubroff and Reid did not consider that the major portion of apparent hydralazine in human plasma is present as labile conjugates (with pyruvic and α-ketoglutaric acids and acetone) (*5*). (iv) Hydralazine is unstable at pH 7.4 and 37°C (*6*). Between 0.5 and 28 days (*1*),