Seeing the noise

Does visual noise affect visual sensitivity?

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Abstract

Random fluctuations, visual noise, pervade every stage of our visual system, from eye to brain. Yet we are hardly ever aware of this noise, and there is great controversy as to whether it limits what we can see. We explored a special condition under which people see their own internal noise and we prove that this noise limits what they see, both under the special conditions and in normal conditions as well. This removes the main obstacle to establishing a simple comprehensive account of visual sensitivity.

Introduction

From reading highway signs to hunting, visual sensitivity is crucial to survival. Sighting a golf hole from a distance, stargazing, and even finding the way to the bathroom at night all demand a sensitive visual system. Human vision is remarkably versatile. We can see over a vast range of luminances, more than a million to one, from bright daylight to starlight. However, our sense of sight does have limits. Anything can be made too small or too faint to see. What determines that limit?

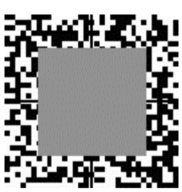
Visual sensitivity is the ability to detect stimuli, and is defined as the reciprocal of threshold contrast. A person with high visual sensitivity can detect low-contrast stimuli. Since Fechner (1860), vision science has sought to explain visual sensitivity. Over 150 years, we have gained major new insights into the physics of light absorption, the parallel visual pathways in the brain, and the way that neurons communicate with each other. However, these advances have not brought us closer to the goal of providing a simple explanation of visual sensitivity. Alas, that goal has receded, as each year's account is more complicated and open-ended than the last.

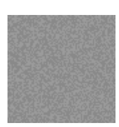
Two key ideas, visual noise and gain, mentioned already by Fechner (1860), are the focus of controversy. Visual noise is any random visual stimulus. We looked at white noise, which is like the dynamic salt and pepper 'static' one sees on a television after transmission ends. Gain is the ratio of output to input, and is like the audio control on a home stereo. It is clear that the gain of the visual system is luminance-dependent. Presented with a bright or dim object, the visual system compensates by reducing or increasing its gain, so that the internal response varies much less than the external stimulus. When gain is reduced sensitivity is lower. Many scientists take that to be the whole story; luminance-dependent gain explains sensitivity. However, way back in 1860, Fechner posited that random fluctuations could be limiting what we see. Rose and Barlow and the Theory of Signal Detectability have since shown that random fluctuations place an upper bound on sensitivity. We rarely, if ever, see this noise because it is too faint. It is hardly surprising that many scientists are skeptical about the idea that the fluctuations of visual noise could be big enough to limit vision yet too faint to see.

Random fluctuation, or "noise", pervades every part of the visual system, but many scientists doubt that it limits what we see. In particular, it has been hard to believe that the limiting factor in visual sensitivity, could be an internal noise that we hardly ever see. Here, we explore a special condition in which observers see an internal noise. We prove that this seen noise limits their visual sensitivity and, further, that sensitivity is normally limited by the same noise even when it is unseen, as in ordinary life.

If this internal noise is really there, perhaps there is a way to make it visible. We think that an adjustment in gain is necessary to see the internal noise. The term *gain* means the ratio between output and input and was often used by television and radio engineers in the 1940's when discussing the ratio between the input and the amplitude of the signal. We will present a case where an increase in gain explains why we can suddenly see noise we couldn't see before: the output, our perceptual experience, is stronger with respect to strength of the input or signal, in this case our internal noise.

So how can we increase the visual system's gain? Ramachandran and Gregory (1991) present an interesting case where observers can see a visual phantasm of noise after adaptation. They describe the phantasm as a result of a "filling in" mechanism, but we think this is actually an instance of observers seeing their own internal noise. We think that the apparition isn't being spontaneously created, but we are simply able to see something that was there all along because of the adaptation. In the paradigm presented in Ramachandran and Gregory (1991), observers fixate somewhere in a field of dynamic noise for one minute, with a gray patch or "artificial scotoma" somewhere in the field. After about a minute, the gray patch appears to "fill in" with the surrounding noise, and the field appears to be filled with noise.





At this point, the field of noise is replaced by a uniform blank field with the same mean luminance. In this blank field, observers report seeing a "phantasm" (Ramachandran & Gregory, 1991; Morgan McEwan & Solomon, 2003), a twinkling patch in the blank area that was formerly surrounded by the field of noise. Studies of the filling-in process (seen while the surrounding noise is present) and the "phantasm" aftereffect (seen after the surrounding noise is removed) initially supposed that the phantasm is the lingering trace of the filling in. Filling in is the process in which peripherally viewed stimuli fade out from view during strict fixation to match their surround (Anstis, 2006). However, parametric studies of the two effects reveal dramatic differences that suggest the two effects require distinct explanations (Hardage and Tyler, 1995; Tyler and Hardage, 1998). Only the aftereffect concerns us here.

Our goal was to show that what we see, the twinkly phantasm, also limits what the observer can detect. To do this we designed a procedure that would corroborate other research that detection is limited by internal noise, a grating detection threshold experiment outlined below. We also created an experiment to show that the internal noise we can see, the twinkly phantasm is the same as the noise limiting detection. Our findings should prove pivotal in the noise versus gain controversy among vision scientists, strongly in favor of a noise-limited theory of visual sensitivity.

Materials and Methods

Stimuli

All stimuli were presented on a cathode ray tube (CRT). We used a ViewSonic UltraBrite E90f+, at a resolution of 832x624, 75 Hz, 60 dot/inch, and a background luminance of 50 cd/m^2. The experiments were programmed in MATLAB with the Psychophysics Toolbox extension (Brainard, 1997; Pelli, 1997).

All trials were conducted at a viewing distance of 63 cm. The observers wore their optical corrections. All viewing was monocular, through a 1 mm artificial pupil from inside a light-tight booth. The artificial pupil was carefully centered on the observer's natural pupil (right eye). The observers used a bite bar (with dental impression compound) attached to a machinist's X-Y platform to maintain stable head position. The X-Y translation of the platform was used to move the observers' head and eye left and right and up and down to align the centers of the natural and artificial pupil. There were two conditions, high and low retinal illuminance. Both used the same 50 cd/m^2 display, viewed through the same 1 mm pupil, with or without a 1.1 neutral density filter, which attenuated the light by a factor of $10^{-1.1} = 0.08$.

The dynamic visual noise of the adaptor were guided by the suggestions of Tyler and Hardage (1998) to optimize the strength of the induced phantasm. Check size of 0.15 deg (4 pixels). Check duration of 0.0268 s (2 frames). The adaptor was 8 deg x 8 deg, except for a 3 deg x 3 deg blank area at its center. RMS contrast was 0.8. Four fixation lines, in the region of the adaptor, pointed to the center of the blank area. The observer was asked to fixate that point throughout the entire experiment.

We tested the observer in the 3 deg x 3 deg area centered on fixation. This was always blank while the adaptor was present. When we displayed noise in the test area, the noise checks of the dynamic noise were 0.0.038 deg (1 pixel) with a check duration of 0.0134 s (1 frame). This noise was presented for 800 ms and accompanied by a 100 ms beep, temporally aligned by their mid-times. When we displayed a grating in the test area, it had a spatial frequency of 8 c/deg and a space constant of 0.19 deg (to 1/e).

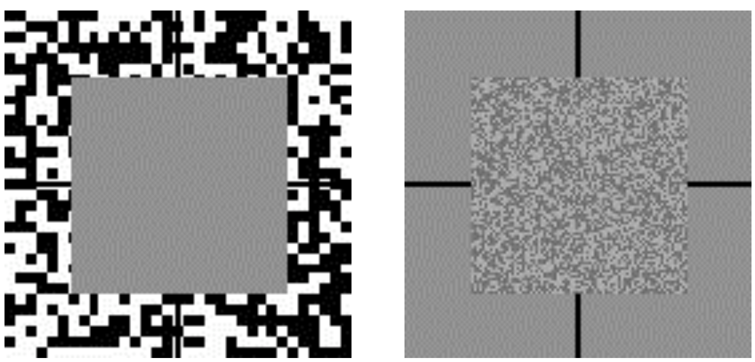


Fig. 2- In the contrast matching experiment, we induced a phantasm with a noisy adaptor (right). We then displayed white noise in the test area (left), and asked observers to rate the contrast of the combination of the phantasm and display noise with blank background.

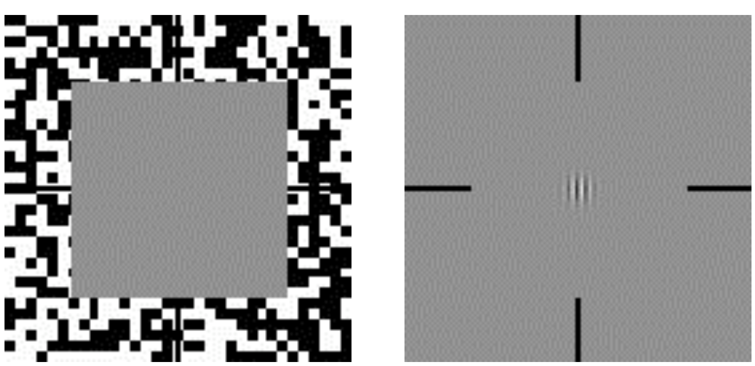


Fig. 3- In the grating detection experiment, we induced a phantasm with a noisy adaptor (right), as in the contrast matching experiment. We then displayed a grating in the test area, and asked observers to report whether grating was horizontal or vertical to test for detection.

Observers

Two observers, EPK and MVK, were used for both experiments. Both gave informed consent. MVK is 15 and EPK is 17.

Procedure

Experiment 1: Threshold for detecting a grating

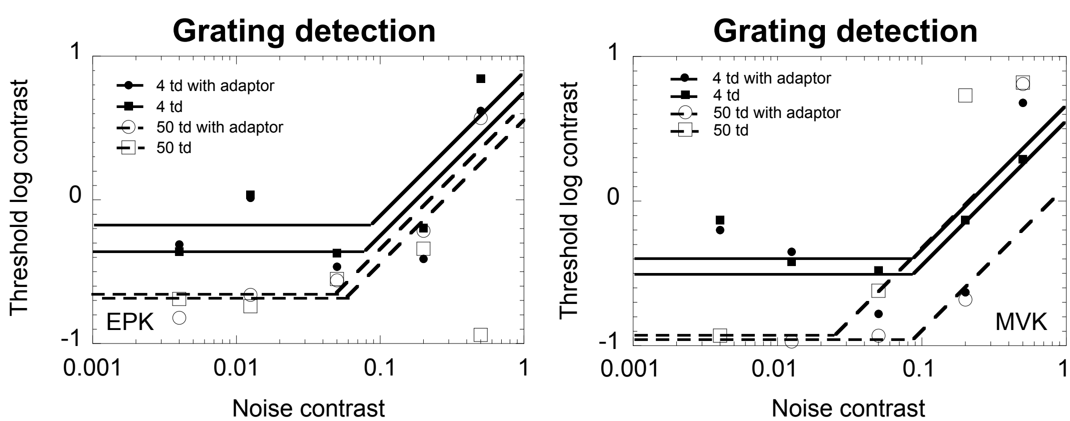
In this experiment, we initially expose observers to an adaptor, a field of dynamic noise surrounding a blank gray patch (see **Fig. 2**). Then, we present a test pattern of a grating in noise within the previously blank patch. We measure threshold contrast c for the grating as a function of the noise N that it is displayed in. We repeat the experiment without the phantasm adaptor to test the effect of adaptation.

Experiment 2: Apparent contrast of noise

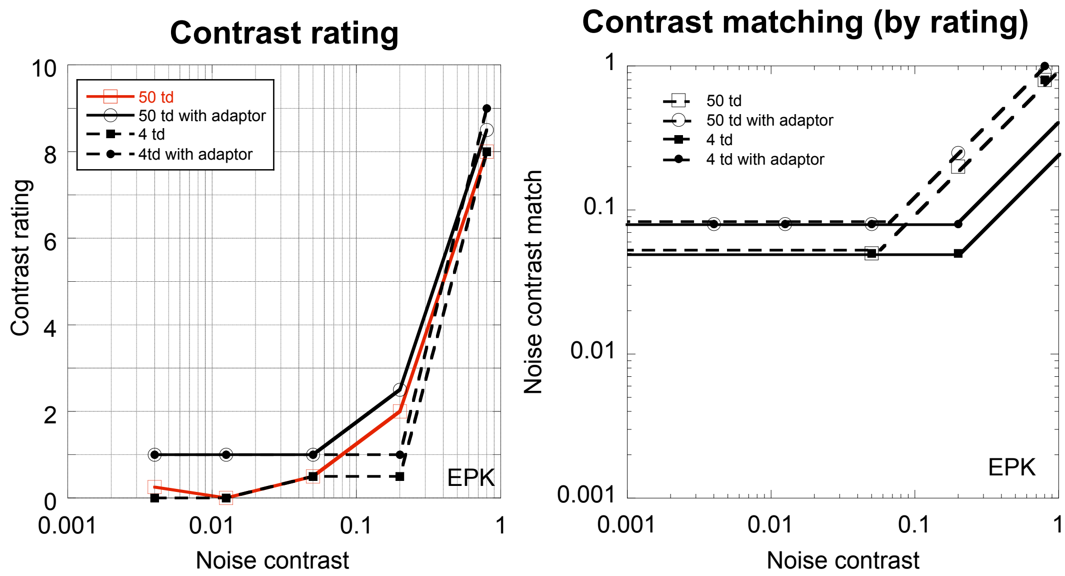
In this experiment, subjects are first presented with the same noisy adaptor described above, then with a noisy patch in the test area (see **Fig. 2**). Observers were then asked to rate the noise of the combination of the phantasm and the display noise in the test area on a scale of one to ten. We plot these ratings as a function of noise contrast. We convert each rating to the noise contrast (50 td, no adaptor) that would yield the same rating (see **Figs. 4 and 5**). We repeat the contrast matching experiment without prior adaptation to test the effect of the adaptor.

Results

We measure contrast threshold for a grating as a function of noise contrast, with and without prior adaptation. We also calculate noise contrast matches as a function of noise contrast based on contrast ratings of noisy patches (see **Fig. 2**). In the results for the grating detection, an increase in gain nicely explains the difference in results between the unadapted and adapted conditions. We find little effect of luminance on threshold contrast for detecting a grating.



For the contrast matching experiment, the data show an increase in equivalent noise at lower luminances and support an increase in gain with the adaptor. It is important to note the factor of 2.8 horizontal shift, for reasons that will be discussed in the next section.



Discussion

Our goal was to show that internal noise limits our sensitivity, and that we can see this internal noise. Seeing the noise is important because many have found it hard to accept that noise could be both a fundamental limit to of our vision and yet invisible, inaccessible to experience. Beyond question, the phantasm is a manifestation of internal noise; it occurs when the external noise is long gone. Some researchers have supposed that this phantasm is the result of an active synthesis, a "filling-in" mechanism provoked by the noisy adaptor. Our data suggest that something different is happening in the phantasm: we are seeing something that was already there. We hypothesize that we can now see it because of an increase in gain.

Photon noise, the type of internal noise limiting sensitivity in our experiments, arrives in the visual system already inextricably linked to the signal. Photon noise is a type of internal noise that limits small, dim, brief signals. A change in gain will not affect the signal-to-noise ratio because it both the signal and noise are equally amplified or attenuated. Because detectability of a signal depends solely on the signal-to-noise ratio, gain does not affect signal detection. To show that *noise* affects signal detection instead, a second measurement was necessary, which we discuss below.

The two equivalent noise measurements described in the results section of this paper suggest that the internal noise that we see in the phantasm is limiting what we see. We found that the adapter only affects apparent contrast, not detection. This is consistent with being a change in gain. This interpretation is supported by the difference in apparent contrasts between graphs, with the graph of apparent contrast without an adaptor being translated up because of the gain change. It seems that gain change provides the mechanism that allows us to see stimuli normally too faint to be detected and should allow us to see internal noise if it is there.

At the display noise level at which the observer's added noise contrast match begins to increase in relation to display noise level, the observer is overcoming some internal limiting factor that makes the noise contrast independent of lower displayed levels of noise level. The internal factor is seen to limit apparent contrast below this equivalent display noise level.

In the grating-detection experiment, the results indicate a similar trend of an internal limiting factor, causing contrast threshold to be independent of display noise below a certain display noise, then being overcome at the *same* noise level as in the apparent contrast experiment. This critical noise display level expresses the internal noise as the amount display noise that is equivalent in effect, in this case, in limiting detection. The equality of the two equivalent noise measurements is strong evidence that both detection of a grating and apparent contrast of noise are both affected by the same internal factor, and that it is an internal noise.

In the contrast-matching experiment, the noise level of the match is equal to the internal noise at the critical noise level turning point. In the first part of the graph, when the noisy peripheral match is independent of the rising central display noise. We are seeing the constant internal noise that masks display noise at lower levels. Amazingly, the equal equivalent noise measurements across the two experiments indicate that this noise that we *see* must be the same noise that limits our sensitivity in grating detection.

Conclusion

Noise does affect our visual sensitivity. We *can* see our internal noise, as evidenced by the phantasm. Because the equivalent noise measurements were the same in the first two experiments, we have strong evidence that our sensitivity is mediated by our internal noise.

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