Contrast sensitivity for oriented patterns in 1/f noise: Contrast response and the horizontal effect

Andrew M. Haun
Department of Psychological and Brain Sciences, University of Louisville, Louisville, KY, USA
Schepens Eye Research Institute, Boston, MA, USA
Edward A. Essock
Department of Psychological and Brain Sciences, University of Louisville, Louisville, KY, USA

When observers detect an oriented, broadband contrast increment on a background of 1/f spatial noise, thresholds will be lowest for obliquely orientated stimuli and highest for horizontally oriented stimuli—an anisotropy termed the “horizontal effect.” Here, we assessed what spatial frequencies within the broadband increment were relied on by observers in performing the original task and which spatial frequencies contribute to the anisotropic performance. We found that against a background of 1/f noise, contrast thresholds are lowest for content around 8 cycles per degree, and that at this spatial frequency a horizontal effect is seen which closely resembles the anisotropy observed in broadband masking. The magnitude of the horizontal effect decreased at lower and higher spatial frequencies. To allow for a fit to a standard “gain control” model of psychophysical contrast discrimination, threshold-versus-contrast (TvC) functions were measured for the 8-cpd noise broadband content against either an identical pattern (i.e., pedestal) or a broadband 1/f noise pattern, whose contrast was varied. Results and model application indicate that the threshold pattern for oriented noise around 8 cpd, and for oriented broadband content, is best explained as the result of an anisotropic contrast gain control process.

Keywords: contrast gain, horizontal effect, contrast sensitivity, masking, oblique effect, orientation


Introduction

When asked to match the perceived magnitude of oriented broadband patterns, subjects respond as if contrast is perceived as weakest at horizontal and strongest at oblique orientations (Essock, DeFord, Hansen, & Sinai, 2003; Hansen & Essock, 2005, 2006; Hansen, Essock, Zheng, & DeFord, 2003). This effect is seen only if the pattern is sufficiently broadband (Hansen & Essock, 2006). Similarly, when oriented broadband patterns are presented as increments superimposed on oriented or isotropic broadband backgrounds, observers need most contrast to detect a horizontal increment and least to detect an increment at oblique orientations (Essock et al., 2003). Finally, when asked to detect narrowband patterns (i.e., sinewave gratings) masked by oriented broadband noise, or by isotropic noise (unpublished data), horizontal thresholds are highest, with obliques typically lowest (Essock, Haun, & Kim, 2009; Kim, Haun, & Essock, 2010). This anisotropy obtained with broadband content, termed the “horizontal effect,” is markedly different from the well-known “oblique effect” (worst performance at oblique orientations) typically found in contrast sensitivity for grating stimuli (e.g., Essock et al., 2009). We have proposed that the horizontal effect is the result of anisotropically weighted contrast gain control that is revealed when the visual system is exposed to broadband spatial structure (Essock et al., 2009; Hansen & Essock, 2006; Hansen et al., 2003). Given the strong link between perceptual contrast response, contrast sensitivity, and perceived contrast—a common functional description can be applied to contrast sensitivity (Chen & Foley, 1997; Foley, 1994), perceived contrast (Cannon & Fullenkamp, 1991), and physiological response (Boynton, Demb, Glover, & Heeger, 1999; Kwon, Legge, Fang, Cheong, & He, 2009)—the existence of a horizontal effect anisotropy in both contrast threshold and suprathreshold appearance strongly indicates that the horizontal effect is related to an anisotropic internal response to oriented broadband contrast (Essock et al., 2003, 2009; Hansen & Essock, 2004).

Natural scenes generally have broadband Fourier spectra where amplitude is closely related with the inverse of spatial frequency (Field, 1987). Noise with this same 1/f amplitude–frequency relationship (“pink noise”), with its structurally neutral appearance (Brady & Field, 1995), has found widespread use in vision science as a proxy for images of real-world scenes (Clarke, Green, Chantler, & Emrith, 2008; Kayser, Nielson, & Logothetis, 2006; Rajashekar, Bovik, & Cormack, 2006). Prior studies using 1/f noise as a visual stimulus (Essock et al., 2003, 2009; Hansen & Essock, 2006) have led to the conclusion that the horizontal effect is caused by anisotropic contrast gain control which is strongly stimulated by broadband stimuli.
A related hypothesis (Hansen et al., 2003) suggests that orientation anisotropies in real-world imagery (Hansen & Essock, 2004; Kiel & Cristobal, 2000) are normalized (Schwartz & Simoncelli, 2001; Wainwright, 1999) by anisotropically weighted contrast gain control mechanisms similar to those described empirically by (Foley, 1994; Meese & Holmes, 2007; Petrov, Carandini, & McKee, 2005; Ross & Speed, 1991). The anisotropy of content in typical natural scenes consists of a relatively constant horizontal contrast peak across spatial frequency, presumably largely from foreshortening and horizon lines, and a vertical peak which is more variable with spatial frequency and more dependent on coincidental image content (cf. Hansen & Essock, 2004; Kiel & Cristobal, 2000; Switkes, Mayer, & Sloan, 1978). A different pattern is seen in cortical neurophysiology. Cortical neurons that are tuned to horizontal or vertical orientations are more prevalent than those preferring oblique orientations, in several species including primates (Coppola, White, Fitzpatrick, & Purves, 1998; Kennedy, Martin, Orban, & Whitteridge, 1985; Mansfield, 1974; Mansfield & Ronner, 1978; Yu & Shou, 2000), and human evoked potentials and fMRI responses show a stronger response to horizontal and vertical gratings (Furmanski & Engel, 2000; Maffei & Campbell, 1970; Zemon, Gutowski, & Horton, 1983). Across spatial and temporal parameters, this bias is seen to be greatest in cells preferring higher spatial frequencies (and lower temporal rates) in the central visual field (Leventhal & Hirsch, 1977; Mansfield, 1974), similar to the human behavioral effect (Berkeley, Kitterle, & Watkins, 1975; Camisa, Blake, & Lema, 1977; Campbell, Kulikowski, & Levinson, 1967; Essock & Lehmkuhl, 1982). More recent studies indicate that this numerical bias is greater for horizontal than for vertical (Coppola & White, 2004; Li, Peterson, & Freeman, 2003). Thus, if one assumes that neurons tuned to similar spatial and temporal frequencies contribute most to a neuron’s gain-control pool (Heeger, 1992), such a numeric anisotropy would predict a larger horizontal effect at higher spatial frequencies. One purpose of the present study was to assess the horizontal effect across spatial frequency in order to compare the findings to these two predictions: whether the anisotropy is found at all spatial frequencies (like the bias in scene content), mainly at high spatial frequencies (as with the physiological bias), or whether something altogether different, and unpredicted, occurs.

In the present study, we measured observers’ contrast sensitivity for 1-octave bands of oriented spatial noise at five spatial frequencies either in isolation or in the presence of a phase-matched broadband isotropic noise pattern. Against a mean-luminance background, contrast detection thresholds for a grating tend to be lowest at a spatial frequency around 2–4 cpd. However, on a background of 1/f, “equal-octave” spatial noise, the sensitivity peak is sharpened and shifted toward higher spatial frequencies (Bex, Solomon, & Dakin, 2009; Schofield & Georgeson, 2003), as the amount of threshold elevation increases with decreasing spatial frequency—naturally, this has implications for sensitivity to more-natural broadband targets. In the experiments detailed here, we describe the pattern of orientation bias in contrast sensitivity for different bands of spatial frequency of oriented structure, both with and without 1/f broadband noise.

### Methods

#### Equipment

All stimuli were displayed on a monochrome (white P104 phosphor) Image Systems, Inc. M21LMAX CRT monitor running at a resolution of 800 × 600 at 200 Hz, with a mean luminance of 30 cd/m². A Vision Research Graphics, Inc. grayscale extender (Pelli & Zhang, 1991) was used to produce 12.4 bits of grayscale resolution (6708 levels). Stimuli were generated using Matlab 7.4 (MathSoft, Inc.), and experiments were carried out using a PC running Matlab 7.4 with the Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997). All stimuli were circular, 5 degrees and 512 pixels in diameter, and were viewed foveally from a distance of 260 cm in a dark room through a circular, 5.2 degree aperture in a large mask fixed to the monitor bezel (blocking view of monitor and room contours).

#### Stimuli

Stimuli included oriented narrowband noise targets; isotropic, broadband 1/f noise patterns; and oriented narrowband pedestal patterns. Target stimuli were oriented, 1-octave noise images, with a triangle-weighted orientation profile 22.5° wide at half height. Background stimuli consisted of 1/f noise and were not oriented (isotropic) and contained a broad range of spatial frequencies (from 1 to 128 cycles per picture; 0.2 to 25.6 cycles per degree). Pedestal stimuli were similar to the targets in being oriented and containing only a narrow range of spatial frequencies but did not contain an orientation peak, rather a band of equal-contrast orientations. A general schematic is provided in Figure 1.

The 1/f noise has equal spectral power in each multiplicative spatial frequency interval (Field, 1987). By Parseval’s theorem, each octave of spatial frequency content in a 1/f noise image will have the same contrast by a variety of measures, particularly root-mean-square (RMS) contrast (here taken as the standard deviation of unit-scale pixel luminances). To take advantage of this property at different spatial frequencies and orientations, we constructed our stimuli in the spatial domain by adding together equal numbers of random-phase sinewave gratings within frequency-domain sectors (in the Fourier
domain, the intersection of an oriented radial “wedge” and a band-pass annulus). Each sector was centered at one of six spatial frequencies (including 0.28, 0.65, 1.50, 3.44, 7.90, and 18.25 cpd) and at one of four orientations (0, 45, 90, and 135 degrees clockwise from vertical). A sector contained 6 sinewaves of different spatial frequencies, spaced 0.2 octaves apart, so that the highest and lowest spatial frequencies were 1 octave apart (since each sector was spaced 0.2 octaves apart from each other sector, this arrangement made use of a 7 octave range of spatial frequencies). For every sector, each spatial frequency was added at 15 orientations, including the center orientation and 7 orientations at 3 degree steps clockwise and counter-clockwise from the center. Every sinewave component had the same amplitude when added to its respective sector. Hence, each sector was the sum of 90 random-phase equal-amplitude gratings. Twenty copies of each sector, each with different random phase structure, were generated for use in these experiments. Each of the five highest spatial frequency sectors were used as test stimuli; for practical reasons having to do with its very low spatial frequency (0.28 cpd) and the randomization of stimulus phase from trial to trial, the lowest sector was not used as a test stimulus in the main experiments. Figure 2 illustrates example sectors at all five test spatial frequencies and four orientations.

A single sector could be used as a pedestal stimulus, as in Experiment 3 (Figure 1d). Adding all sectors together across spatial frequency and orientation produced an isotropic, 7-octave, broadband noise image with structural spatial characteristics visually indistinguishable from those of a 1/f noise pattern produced through an inverse Fourier transform. The two types of image (the linear-frequency Fourier images and our log-frequency summed images) are conceptually equivalent: each contains an equal volume of contrast or amplitude in each octave (Brady & Field, 1995). These steps were taken largely in order to avoid the problem of limited orientation resolution in the low-frequency portion of the Fourier domain in discrete approximations (Hansen & Essock, 2004; cf. Essock et al., 2009).

Target stimuli were constructed similarly, except that amplitudes were weighted in the orientation dimension with a triangular profile, peaking at the center orientation and declining to 1/7 of peak amplitude at 21° from the center orientation (then truncated, producing a 43° wide band). This was done for three reasons: to emphasize the center orientation for a given target stimulus, to obviate an

Figure 1. Frequency/orientation domain plots represent content present in conditions of different combinations of targets and masks. Z-axis represents sector contrast as described in Methods. (a) Experiment 1. A broadband (spatial frequencies from 0.2 to 25.6 cpd), oriented (45° band) target was detected against an isotropic, broadband background. (b) Experiment 2 baseline condition. A 1-octave narrowband (1.5 cpd band shown), oriented target (45° triangle band) was detected against a mean-luminance (zero-contrast) background. (c) Experiments 2 and 3 masking condition. A narrowband, oriented target was detected against an isotropic, broadband background whose contrast varied. (d) Experiment 2 and 3 increment threshold condition. A narrowband, oriented target was detected against a narrowband, oriented background with matched characteristics.
illusion that is stronger with spectrally rectangular stimuli (Essock, Hansen, & Haun, 2007), and to make our stimuli structurally similar to those used in earlier studies of broadband orientation effects (e.g., Essock et al., 2003, Hansen & Essock, 2006), which used triangular oriented amplitude increments. Figure 3 shows example target sectors added to a phase-matched broadband background.

**Stimulus conditions**

Four distinct stimulus conditions were included. Experiment 1 aimed only to replicate the aforementioned broadband horizontal effect (Essock et al., 2003) and determine comparison values. For each orientation, sectors of all six spatial frequency bands were added together to create an oriented broadband target stimulus, and contrast thresholds were measured for the target at each of the four orientations against a background of isotropic, broadband noise (consisting of all 24 mask sectors added together) as shown in Figure 1a. The phase structure of the target stimulus was matched to the corresponding structure in the background stimulus. Example stimuli at four orientations are shown in Figure 4a.

For the Experiment 2 baseline condition, narrowband contrast sensitivity was measured by obtaining contrast...
thresholds for the target sectors against a mean-luminance background (Figure 1b). Next, contrast sensitivity was measured for these targets against a background of isotropic $1/f$ noise (Figure 1c). The RMS contrast of the $1/f$ background was fixed at 0.12 (but note the final paragraph in this section, and Appendix A). Again, the phase of the target was matched to the phase of the corresponding content in the background stimulus.

Figure 3. (a) Broadband noise image produced through summation of sectors such as those illustrated in Figure 2, plus additional content in one lower frequency octave (0.2 to 0.4 cpd). (b) Target stimuli added to the broadband background shown in “a.” The pattern is, representative of masked targets used in Experiments 2 and 3.
For the Experiment 3 baseline and in the second part of Experiment 2, narrowband contrast increment thresholds were measured for the target sectors against a phase-matched background consisting of only the same frequencies and orientations as those in the target band (i.e., against the same sector; Figure 1d). For the Experiment 3 masking condition, the same target and pedestal conditions were used as with the baseline, but with the other 23 mask sectors varied along with the pedestal sector: in other words, the entire broadband isotropic pattern was used as a contrast-variable pedestal for the narrowband target sector (Figure 1c).

Contrast values for these stimuli could be described by numerous conventions. One difficulty with the stimuli in this study is in referring to the contrasts of the narrowband targets and the broadband masks with common terms. All contrast values cited herein refer to the root-mean-square contrast (the standard deviation of the normalized pixel luminances) of the individual mask sectors, in decibel (dB) units. If, as in the “increment threshold” task in Experiments 2 and 3, a single mask sector was used as a background, the average RMS contrast of that sector is cited (since each sector has a random phase structure, some small fluctuation in physical contrast occurred from trial to trial, dependent on spatial sample area). If all 24 mask sectors were used to create an isotropic background as in the “broadband masking” conditions of Experiments 2 and 3, the average RMS contrast of the 24 component sectors was cited. A contrast-measure “look up table” is provided in Appendix A.

Procedure

A 2IFC paradigm was used, with sequential 500-ms stimulus intervals separated by a 500-ms inter-stimulus interval (Subject S1 completed all experiments with 750 ms stimulus interval duration). A QUEST algorithm (Watson & Pelli, 1983) was used to measure 82% correct contrast thresholds at each orientation and spatial frequency for each stimulus condition. Each QUEST run consisted of 40 trials, and if the procedure failed to converge by the 40th trial (if the standard deviation of the QUEST function failed to reach a predetermined limit of 0.08 log units), the measure was discarded and the procedure repeated: the limit was normally reached in less than 40 trials. Each data point represents the mean of at least three QUEST function modes acquired during separate sessions. During a given session, observers completed a single instance of one stimulus condition: all spatial frequencies at one background contrast (Experiment 2) or all background contrasts at one spatial frequency (Experiment 3). A block of trials consisted of four QUEST procedures, each with a differently oriented target but otherwise identical conditions, performed in random order.

Participants

For Experiments 1 and 2, five observers participated, including one of the authors (S1), one other experienced psychophysical observer (S4), and three subjects entirely naive to the purposes of the experiment (S2, S3, and S5). In Experiment 2, the same five observers participated but one of the naive observers was tested only at the three highest spatial frequencies, whereas the other four completed all five frequencies. In Experiment 3, the four participants included one of the authors (S1), one of the three naive observers who participated in Experiments 1 and 2 (S2) and two other experienced observers naïve to the purposes of the experiments (S6 and S7). All observers had normal acuity and no significant astigmatism (wearing any needed correction), were between the ages of 19 and 29, and were treated according to IRB guidelines including giving informed consent.
Results

Experiment 1: Detecting oriented broadband increments against a 1/f background

Observers detected broadband, oriented contrast increments on a phase-matched 1/f noise background (cf. Essock et al., 2003) to establish a broadband horizontal effect for comparison. A horizontal effect was obtained for all subjects, with thresholds highest for horizontal, and generally lowest for the obliques (Figure 4b). Vertical thresholds were comparable to oblique thresholds overall, varying with individuals. The size of the effect, measured as the difference between horizontal and oblique thresholds, averaged 3 dB. This is similar to or slightly larger than the anisotropy of suprathreshold apparent contrast measured with similar stimuli in previous studies (around 2 dB measured in Essock et al., 2003, and in Hansen & Essock, 2006). Next, we asked what part of the broadband target stimulus is being used by observers to carry out the broadband detection task.

Experiment 2: Detecting narrowband increments against a 1/f background

Here, oriented 1-octave noise patterns were used as contrast targets. Sensitivity to oriented content was tested at each spatial frequency to observe which spatial frequencies determine the horizontal effect measured with broadband targets. First, contrast thresholds were measured against a mean-luminance background as a baseline. For each orientation and for each observer, contrast threshold as a function of spatial frequency follows a familiar U-shaped function, with sensitivity peaking around 3.4 cpd. Data are plotted for each test orientation (and joined with a solid line) at each spatial frequency (Figure 5a). Each set of four points is plotted at the mean threshold level (across orientation) at each spatial frequency. At the highest frequency (18 cpd) an oblique effect is seen with oblique thresholds averaging 2.22 dB higher than threshold for the averaged cardinal orientations.

The oriented threshold pattern is consistent across observers, although individual differences are apparent (Figure 6, left). Figure 6 (left) shows three measures of orientation anisotropy: cardinal minus oblique thresholds (“oblique effect”), horizontal minus vertical (“horizontal bias”), and right-tilt (45°) oblique minus left-tilt (135°) oblique (“oblique bias”). On the whole, across spatial frequency there are no large orientation effects, until the oblique effect becomes significant at 18 cpd (Figure 6 left, middle). Horizontal effects are not seen here: horizontal and vertical are more or less equal at all spatial frequencies (Figure 6 left, top). The measure of oblique bias (Figure 6 left, bottom) serves as a control as no difference between contrast sensitivity for the two 45° oblique orientations is anticipated, and indeed they are fairly equal with the oblique bias near zero across spatial frequency.

Sensitivity to 1-octave oriented contrast increments on a broadband background

When broadband 1/f noise is added to the target images the contrast threshold function is distorted, with a shifted minimum and an almost linear decline in log contrast thresholds with log spatial frequency until the minimum at the 8-cpd band, after which thresholds rise again (Figure 5b)—the decline of threshold across the lower and
middle spatial frequencies is well characterized by a slope of −0.7 on these axes (dB contrast threshold by log frequency—diagonal dotted line, Figure 5b) for all subjects.

With the broadband mask (Figure 6, right), at every spatial frequency, average horizontal thresholds are higher than vertical thresholds (the horizontal–vertical bias: Figure 6 right, top) by about 1.5 dB. The oblique effect (Figure 6 right, middle) remains at the high spatial frequency (16 cpd) but now reverses (higher thresholds for cardinals) sharply at 7.9 cpd, for an average difference of 2.6 dB. In combination with the horizontal bias, the result is a strong horizontal effect at this spatial frequency (see Figure 5, bottom).

Viewed simply as a contrast masking effect, the steep decline in threshold up to a high spatial frequency is not expected. Contrast constancy (Brady & Field, 1995; Georgeson & Sullivan, 1975) would predict that since each octave of the 1/f mask contains an equal amount of contrast, increment thresholds should become more and more similar the stronger the background contrast. We verified that this flattening does occur with the present...
stimuli (i.e., 1-octave bands) by measuring thresholds in some observers at each spatial frequency, with vertical targets, with only the local (target) content present as a mask (i.e., testing increment thresholds for the target sectors with all non-target sectors set to zero). The contrast of the background images was equated with the contrast of the average sector within the broadband images used previously (cf. Appendix A). In this case, thresholds were indeed constant with frequency (Figure 7, solid lines and filled symbols). Thus, the pattern of thresholds at the different spatial bands produced in the broadband 1/f noise condition (i.e., not flat across spatial frequency; Figure 5b) must be a result of the influence of content in the non-target sectors that make up the remainder of the broadband background pattern.

Also of interest here is the negative difference at 7.9 cpd between these increment thresholds obtained on 1-octave masks and the 1/f-masked thresholds: the broadband noise-masked thresholds (Figure 7; dashed lines, open symbols) are lower than the increment thresholds, meaning that the addition of content at other frequencies and orientations facilitates sensitivity at this frequency. This effect was pursued further in Experiment 3.

Relation to broadband thresholds

Sensitivity to the broadband targets on the broadband background obtained in Experiment 1 (the solid symbols plotted at the far right in Figure 5b) is a little better than the peak of sensitivity for the noise-masked target octaves (Figure 5b), with thresholds around −49 dB as compared with the mean threshold of around −45 dB at 7.9 cpd. The discrepancy is likely due to the fact that perceptual filter bandwidths around 7.9 cpd are broader in the spatial frequency domain than our 1-octave target sectors (Daugman, 1984; Wilson, McFarlane, & Phillips, 1983), allowing for stimulus contrast across several sectors to stimulate one channel. Even with this 4-dB gap, given the presence of a horizontal effect of similar magnitude at the peak of the noise-masked CSF, it seems reasonable to conclude that sensitivity to the broadband stimulus (Experiment 1) is determined largely or exclusively by a set of visual mechanisms tuned to a spatial frequency around 7.9 cpd.

Experiment 3: Detecting narrowband contrast increments on narrowband backgrounds versus 1/f backgrounds

At the 7.9-cpd peak of the 1/f-masked contrast sensitivity function, a horizontal effect is obtained—also at this frequency, sensitivity is better than would be predicted on the basis of increment thresholds. One way to characterize what is occurring at this spatial frequency is by measuring threshold-versus-contrast (TVC) functions for the oriented patterns against the isotropic backgrounds. Comparing TVC functions for narrowband (i.e., similar with the target) and 1/f masks can indicate the type of perceptual change that occurs for the target content in the presence of the mask (cf. Foley, 1994; Yu, Klein, & Levi 2003). For the baseline TVC functions, all mask sectors except the one matching the target sector were set to zero. The contrast of the orientation-, frequency-, and phase-matched “pedestal” background was varied across six (seven for subject S1) levels (Figure 8, top, shows four levels), and sensitivity to the target was measured at each level (depicted in Figure 1d). For the masked TVC functions, the other 23 mask sectors were varied along

Figure 7. Data from the “contrast constancy” test in Experiment 2. Individual subjects’ data are offset for clarity, so dB units are relative. Increment threshold for 1-octave band targets (solid lines and symbols) is very flat with spatial frequency. Open symbols and dotted lines represent mean (across orientation) data from Figure 5 (1-octave bands tested on broadband background). Note that increment thresholds are higher than noise-masked thresholds at 7.9 cpd.

Figure 8. Pedestal background stimuli for Experiment 3. Top row: Baseline background stimuli were vertical, 1-octave sectors as described in Methods. Bottom row: Masking condition background stimuli. Sector contrast (see Appendix A) has been equated between the stimuli in the two rows.
with the pedestal (Figure 1c): in effect, the pedestal was a broadband, isotropic 1/f noise image (Figure 8, bottom). For two of the observers (S2 and S6), only vertical targets were used; for two others (S1 and S7), all four main orientations were used. Individual data are shown in Figure 9a for subjects S2 and S6. Oriented TvsCs for subjects S1 and S7 are shown in Figure 9b.

When only the contrast of the target sector pedestal was varied, with the other sectors set to zero (i.e., an increment threshold task), a typical dipper-shaped Tvc function was measured (solid symbols and lines in Figure 9). When the other sectors were varied along with the target sector pedestal (making for an isotropic broadband pedestal), a nearly proportional degree of facilitation was measured at all suprathreshold contrasts (Figure 9a, open symbols and dashed lines). These results are readily described by the functional model of contrast pattern masking described by Foley (1994) and others (e.g., Chen & Tyler, 2001; Holmes & Meese, 2004; Yu et al., 2003), which is stated here as equivalent with \( d' \):

\[
d' = r \cdot \frac{(c)^{p+q}}{(p+w(m)^p + (c)^q)}. \tag{1}
\]

Here \( c \) denotes a linear measure of contrast, presumably by perceptual filters with properties (spatial frequency, orientation, etc.) matched to the target stimulus; \( m \) denotes a measure of contrasts by filters with properties matched to the non-target content. The parameters \( p, q, r, z, \) and \( w \) are constants determining the overall shape of the function under particular contrast conditions. Model fitting details

---

Figure 9. (a) Results from Experiment 3. Threshold-versus-contrast functions for three observers. Solid symbols are for target detection on narrowband backgrounds. Open symbols are for target detection on broadband backgrounds. Lines are fits to the data using \( \text{Equation 1} \) as described in the text. Data for subjects S1 and S7 have been averaged across orientation. Dotted line is the fit of a modified model to the data, with a higher exponent for the gain control term (see text). (b) Tvc functions for subjects S1 (left) and S7 (right) at four orientations, fitted with \( \text{Equation 1} \) varying \( r \) and \( w \) between orientations (top) or varying \( r, w, \) and \( k \) (bottom). Orientation values indicate degrees clockwise of vertical (0°).
are included in Appendix B, involving minimizing $\chi^2$ between model and data. In the case of Experiment 3, in the broadband-pedestal condition, the non-target sectors drive the term ($m^p$) and thus function as an inhibitory mask whose contrast is varied in tandem with the target pedestal contrast; that is, $m$ was set equal to $c$.

For the subjects who completed the experiment at four orientations, data are presented in Figure 9b. The horizontal effect in masked thresholds can be seen in the high contrast regime of the TVC functions. The value of $w$ varied with orientation in a horizontal effect pattern (Figure 12a, solid symbols; Table 1). However, for the two subjects, we found using a nested model $F$-test (cf. Kwon et al., 2009) that the other parameters could also be varied with orientation to significantly improve the fit to the data (varying $p$ was best for S1, $F(47,44) = 3.00$, $p = .0002$; and varying $r$ was best for S7, $F(55,52) = 3.6$, $p < .001$; conversely, varying $r$ for S1 yielded $F(47,44) = 0.20$, $p = .999$, while varying $p$ for S7 yielded $F(55,52) = 2.0$, $p = .077$). Varying $w$ with orientation was not particularly useful for one of the two subjects (for S1, $F(47,44) = 1.66$, $p = .0463$; for S7, $F(55,52) = 3.20$, $p < .0001$). Table 1 shows best-fitting parameters for the vary-$w$ and vary-$p$ models. The better overall effect of varying $p$ appears to be due to its capacity to describe both the horizontal effect during masking conditions and its capacity to describe the small oblique effect seen at detection in both subjects’ data. No two-parameter model performed as well as the best one-parameter models, so these are not discussed here.

The suprathreshold regime of the masked TVC function is overshot by the model at low contrasts and undershot at high contrasts. This curvature in the data suggests that the rate of increase of inhibition by the noise mask with increases in mask contrast is faster than the term $w(m^p)$. At high mask contrasts, the gain control pool may be fed by many sources, from more-distant spatial frequencies and orientations, or different types of mechanism; at low contrasts, only a few sources might contribute. This increase not only in masking with contrast but also in sources of masking with contrast can be represented by the exponent $p$ in the mask term (i.e., the rate at which mask contrast contributes to the increase in divisive inhibition). To demonstrate this, Equation 1 was refit with an extra parameter $\mu$ which was added to the exponent $p$ in the mask term: $w(m^p)^{\mu}$. Results are plotted as the thin dotted lines in Figure 9a and in the lower panels in Figure 9b. Such a manipulation can capture some of the curvature in the data—no other straightforward means of altering Equation 1 can produce this type of change in the TVC function. We note here that this modification is a means of describing a gain control effect which increases faster than predicted by $p$; however, since the underlying process likely involves progressive recruitment of more and more suppressive inputs to the detecting mechanism, a single parameter is unlikely to hold for different mask configurations and may in fact take a form very different from a wholesale change in the gain control exponent.

The vary-$p$ model is, overall, a slightly better fit to the data than the vary-$w$ model. Figure 10a plots threshold as a function of orientation, as computed by the four models listed in Table 1, showing that this model does accurately describe the horizontal effect of increment threshold shown in Experiments 1 and 2. However, does it also predict the horizontal effects of perceived contrast (salience) measured elsewhere (Hansen & Essock, 2006)? The most straightforward means of estimating perceived contrast in this case is to assume what has been called an unaware decoder (Series, Stocker, & Simoncelli, 2009) for contrast gain control, which suggests that the visual system should interpret suppressed perceptual responses (i.e., $d'$ values which are lowered due to gain control) as lower contrasts, as a function of the unsuppressed response function. Hence, if $f(c, m, \phi) = d'$, where $c$ and $m$ are test and mask contrasts, respectively, and $\phi$ is the set of parameters for a given oriented contrast transducer, the observer should interpret the perceptual response as if it had no knowledge of the gain control process and thereby was ignorant of the effects of $m$ on the perceptual response: $f^{-1}(d', \phi) = C$, where $C$ is perceived contrast. We computed values for $C$ (solving $f^{-1}(d', \phi(p, q, z, r, w, (\mu)))$ numerically for $d' = f(c, m, \phi(p, q, z, r, w, (\mu)))$, with $c = m = -32.2$ dBA for the four models listed in Table 1, at each orientation, with the results plotted in

<table>
<thead>
<tr>
<th>$p(0°, 45°, 90°, 135°)$</th>
<th>$q$</th>
<th>$z$</th>
<th>$r$</th>
<th>$w(0°, 45°, 90°, 135°)$</th>
<th>$\mu$</th>
<th>$\chi^2$</th>
<th>$df$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vary $w$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S1</td>
<td>2.57</td>
<td>.47</td>
<td>.003</td>
<td>75.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.16</td>
<td>.45</td>
<td>.004</td>
<td>70.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vary $w$ (with $\mu$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S1</td>
<td>2.63</td>
<td>.48</td>
<td>.003</td>
<td>77.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.23</td>
<td>.47</td>
<td>.004</td>
<td>73.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vary $p$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S1</td>
<td>(2.08, 2.81, 2.04, 2.48)</td>
<td>.46</td>
<td>.004</td>
<td>71.9</td>
<td>0.44</td>
<td>92.50</td>
<td>52–9</td>
</tr>
<tr>
<td></td>
<td>(1.91, 1.5, 1.36, 1.52)</td>
<td>.44</td>
<td>.005</td>
<td>72.6</td>
<td>0.41</td>
<td>58.59</td>
<td>60–9</td>
</tr>
<tr>
<td>Vary $p$ (with $\mu$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S1</td>
<td>(2.12, 2.13, 2.14, 2.67)</td>
<td>.47</td>
<td>.003</td>
<td>92.3</td>
<td>1.00</td>
<td>85.93</td>
<td>52–9</td>
</tr>
<tr>
<td></td>
<td>(2.1, 2.73, 1.75, 2.18)</td>
<td>.47</td>
<td>.004</td>
<td>73.1</td>
<td>0.55</td>
<td>59.80</td>
<td>60–9</td>
</tr>
</tbody>
</table>

Table 1. Best-fit parameters, as described in the text, for Equation 1 to the data shown in Figure 9. Both vary-$w$ and vary-$p$ models afford reasonable fits to the data. $\chi^2$ is calculated as described in Appendix B. df are equal to the number of fitted data points minus the number of model parameters.
Facilitation by excitation

Another explanation for the general pattern of facilitation seen in the masked Tvc functions is that pedestal contrast c is being attenuated by the mask (cf. Georgeson, 1985) before the non-linearities represented by the exponents p and q:

\[ d' = r \cdot \frac{(c + h \cdot m)^{p+q}}{c + h \cdot m} \cdot \]  

(2)

If h is a value between -1.0 and 0.0, test contrast will be attenuated (recall that c and m are equated in these experiments), and the Tvc function will be stretched out along the ordinate axis toward higher contrasts, thereby producing lower discrimination thresholds. This sort of change does resemble the data shown in Figure 9 (Figure 11, dashed curve in the top row at 7.9 cpd).

As shown in Experiment 2, masked thresholds at lower spatial frequencies were elevated relative to local increment thresholds. To achieve the same result with the h model, h must be a positive value. This represents a plausible source of masking, whereby mask contrast stimulates the same mechanisms used to detect the test pattern, pushing them into their compressive transduction regime. With threshold elevations increasing with...
decreasing spatial frequency, $h$ must also increase with decreasing spatial frequency. Again, this is plausible since spatial bandwidths increase towards low frequencies, which would allow more mask content to be pooled together with target content toward low spatial frequencies (cf. Schofield & Georgeson, 2003). Figure 11 shows hypothetical masked (dashed lines) and baseline (solid lines) TvC functions at different spatial frequencies. The top row, masking is produced through the $w$ model, along the middle row through the $h$ model. At high contrasts, predicted threshold patterns are very similar for the two models, but the prediction is different at low contrasts, where the masked and baseline functions cross for the $h$ model but not for the $w$ model. This low-contrast divergence of the two models at low spatial frequencies is even more pronounced if the contrast of the mask is fixed at a high level (dotted lines): while masked TvC functions with the $w$ model are greatly elevated and retain their dipper shape at lower spatial frequencies, $h$ masked functions lose their dipper shape at low spatial frequencies and become facilitated at low contrasts—the masked TvC function is, in effect, starting at the bottom of the dip, from where it can only increase as test contrast is increased. Such a large difference in threshold patterns is easily measured. One of the authors (S1) repeated the increment threshold task at each spatial frequency, with an added condition including non-target mask content fixed at the same contrast used in Experiments 1 and 2 (−32.2 dB). Results are shown in Figure 11 (bottom row). Clearly, there are substantial masked dipper functions at all spatial frequencies—if $h$-type effects occur at lower frequencies, they are swamped by a more $w$-like effect, although the case is more ambiguous at 7.9 and 18.25 cpd and the problem warrants deeper analysis in another context.

**Model application to Experiment 2**

Although TvC functions were not measured at other spatial frequencies for most subjects, the model described above can be adapted to fit the threshold data obtained in Experiment 2 and estimate $w$ values for those observers. Details are given in Appendix B and involve fixing parameters $r$, $p$, and $q$ across spatial frequency and orientation for all observers, fitting a CSF function (Watson & Ahumada, 2005; Yang, Qi, & Makous, 1995) to $z$, implementing a parameter for each observer that reflects the oblique effect (Watson & Ahumada, 2005), and searching for best-fitting values for the “gain control” parameter $w$. Results are shown in Figure 12a (by orientation) and Figure 10b (by spatial frequency) and
suggest that if gain control is responsible for the masking effects seen in Experiment 2, it is progressively more intense towards lower spatial frequencies. The difference in magnitude of \( w \) between subject S1 and the others is likely due to the longer stimulus intervals viewed by that subject (750 versus 500 ms). The magnitude of the gain-control weight \( w \) is seen to vary with test orientation, with the weight at horizontal being quite large and the weight for oblique tests much less (Figure 12).

It is worth noting explicitly that the facilitation shown in Experiments 2 and 3 is an instance of the “dipper crossing” (Figure 13a) noted by previous authors (see Foley, 1994; Greenlee & Heitger, 1988; Meese & Holmes, 2007; Ross & Speed, 1991) and can be taken as a hallmark of the gain control hypothesis of contrast masking (including the relatively less explanatory, subtractive \( h \)-type model): the steeper, low-contrast regime of the \( d' \) function is being shifted to higher contrasts (Figure 13b), thereby reducing increment thresholds. Neither channel uncertainty produced by the broadband nature of the \( 1/f \) stimulus (Pelli, 1985) nor noise masking (Lu & Dosher, 1999; Schofield & Georgeson, 2003) would be expected to produce facilitation of increment thresholds. Furthermore, stochastic resonance (Blackwell, 1998; Goris, Wagemans, & Wichman, 2008; Sasaki et al., 2008), the phenomenon whereby a certain amount of noise facilitates performance of a complex system, would be expected to occur only for a certain level of background noise; however, in the case of these stimuli, the facilitation seems to occur over a broad range of background noise contrasts.

**Discussion**

**The broadband CSF**

The presence of \( 1/f \) noise both alters the shape of the CSF and results in a markedly different pattern of orientation anisotropy. Threshold facilitation is seen around 7.9 cpd, while masking towards lower spatial frequencies is progressively greater than would be expected from within-mechanism masking alone (Figure 7). The threshold effects at 7.9 cpd are particularly interesting for two reasons. First, it is at 7.9 cpd where the most robust horizontal effect is measured with these stimuli. Since the peak of sensitivity in \( 1/f \) noise seems to be at or near the

![Figure 12](https://jov.arvojournals.org/pdfaccess.ashx?url=/data/journals/jov/932797/)

**Figure 12.** \( w \) values from model fits. Left: Oriented \( w \) values obtained in Experiment 3 (subject S1, solid symbols) or in Experiment 2 (open symbols) show horizontal effects for each subject. Right: \( w \) values as a function of spatial frequency. \( w \) values are progressively greater towards lower spatial frequencies.

![Figure 13](https://jov.arvojournals.org/pdfaccess.ashx?url=/data/journals/jov/932797/)

**Figure 13.** Model outputs. (a) Simulated \( T_{VC} \) functions for a 7.9-cpd target, using mean model parameters from subjects from Experiment 3. Solid symbols and thick line are the “baseline” \( T_{VC} \) function. As mask contrast increases, hypothetical \( T_{VC} \) functions are shifted up and to the right, causing the facilitatory “dip” to cross over the baseline function. Open symbols and the dashed line represent where on the hypothetical \( T_{VC} \) functions thresholds would be measured if baseline and broadband background sector contrasts were equated. (b) \( d' \) functions corresponding to the \( T_{VC} \) functions in panel a. As mask contrast increases, \( d' \) functions are shifted to the right. Open symbols denote where on the hypothetical \( d' \) functions thresholds would occur if baseline and broadband sector contrasts were equated. Note that at these locations, hypothetical \( d' \) functions are steeper than the baseline \( d' \) function, which would produce threshold facilitation. (c) Without gain control, perceptual response (\( d' \)) increases quickly with increasing target contrast, with responses at all spatial frequencies well-above threshold at most contrasts shown. (d) With gain control (i.e., with a broadband mask), responses are greatly attenuated and greatest at 7.9 cpd for high mask contrasts. Note that the CSF peak shifts to 3.5 cpd at lower mask contrasts as seen in Figure 5. Also note the expanded scale of the ordinate in “d” relative to “c.” (e) The effects of a broadband mask on sensitivity as a function of pattern contrast (of test and mask) and gain control weight \( w \). Facilitation (\( Z \)-axis values < 0) is seen at mid-high pattern contrasts, for \( w \) values below 2.0. Higher \( w \) values result in progressively more masking. The red line describes the effect of mask contrast on narrowband sensitivity at a \( w \) value of 1.0, which is near the mean value obtained for subject S1.
same spatial frequency, this means that broadband fluctuations in contrast will have relatively less effect on visual perception if they are horizontally oriented than if they are obliquely or vertically oriented. Second, the suprathreshold facilitation seen at 7.9 cpd appears to be identical with the “dipper crossing” phenomenon noted by some other researchers and predicted by the familiar “gain control” model of contrast discrimination (Figure 13a). This lends further support to our earlier linking of the broadband horizontal effect with the gain control hypothesis of pattern masking, although we could not establish a significant relationship between the gain control factor and the orientation anisotropy itself.

With the model parameters used to fit the Experiment 2 data (Appendix B), model response functions are illustrated in Figures 12c and 12d across spatial frequency. When no broadband stimulus is present (Figure 13c), responses at different frequencies reach threshold (the 1.3 \( \Delta f \) level represented by the horizontal dashed line) at points corresponding to the contrast sensitivity functions measured in Experiment 2 and flatten out at higher contrasts accounting for the basic properties of the data in Figure 5a (the U-shaped CSF) and Figure 7 (contrast constancy). When a broadband mask is present (i.e., gain control is activated; Figure 13d), with increasing stimulus contrast, responses are greatly suppressed and progressively diverge, with responses being greatest around 8 cpd at mid-high contrasts. If identified with perceived contrast, these values suggest that the perceived contrast of broadband 1/f noise pattern should be extremely attenuated: at the highest contrasts, it is predicted that the apparent magnitude of narrowband perceived contrast should be as much as four times greater when viewed in spectral isolation than when viewed as part of a broadband image (note the difference in scale between Figures 12c and 12d ordinates).

In general, thresholds can be increased through response shifting (“contrast gain control” in our terminology; cf. Foley, 1994; Holmes & Meese, 2004), response compression (e.g., Chen & Tyler, 2008; Huang & Dobkins, 2005), and increases in internal or external noise (e.g., Lu & Dosher, 1999). Our stimuli are relatively large and spatially complex, likely activating multiple processes with similar effects on measurements (i.e., raised thresholds), so it is possible that rather than a shifting of the contrast response to higher contrasts through a gain control network, some other mechanism is responsible for much of the masking below 7.9 cpd. The noise-masked response plot in Figure 13d gives an opportunity to test intuitions about how broadband 1/f patterns actually look. At an RMS contrast of 0.12 (−32.2 dB, the background contrast used in Experiments 1 and 2), responses at the lowest spatial frequencies (0.65 cpd or 1.5 cpd) are projected to be at or very near the absolute detection threshold (the horizontal dashed line indicates the point at which content would be seen 83% of the time). If we adopt the additive noise hypothesis of suprathreshold contrast discrimination, this implies that content at these frequencies should be nearly invisible. Simple observation suggests that this low-frequency content is plainly visible in 1/f patterns of contrast lower than 0.12 or at least that 7.9 cpd content is not as perceptually dominant as 12d predicts. If low spatial frequency components are near or below their own detection threshold while still contributing to visible content in the image, this implies that lower frequency mechanisms pool contrasts differently than higher frequency mechanisms. Visibility (and perceived contrast) of low frequencies may be dependent on mechanisms with broader bandwidth than the target stimuli used here, which would be brought above threshold by pooling across multiple sectors. Mechanism responses projected with single-sector contrasts (as was done in Figures 12c and 12d) would therefore be underestimated.

Another possibility was proposed by Schofield and Georgeson (2003), whose study had many similar elements with ours, with observers detecting sine wave gratings of varying spatial frequency masked by 1/f noise patterns. They described their results in terms of equivalent internal noise (Lu & Dosher, 1999; Pelli & Farell, 1999), hypothesizing that the broadening of channel bandwidths towards low spatial frequencies would allow more and more stimulus noise to pass to a decision stage, thereby combining with the observer’s internal noise and depressing the \( \Delta f \) function as a function of channel bandwidth. Such a model is insufficient to explain the facilitation seen at 7.9 cpd, although it does allow for the clear visibility of low spatial frequencies in the 1/f noise patterns, albeit in a probabilistic manner that does not exactly fit subjective impressions of the stimuli. It seems likely that both types of process are at work here: external noise has the potential to decrease sensitivity, while contrast gain control has the potential both to decrease and to facilitate suprathreshold sensitivity, although the present data cannot disambiguate the relative contributions of the two potential sources. Furthermore, our findings are consistent with those of Meese and Holmes (2007), who have shown clearly that contrast masking increases towards lower spatial frequencies in the absence of spatial noise.

The magnitude of the horizontal effect at different spatial frequencies

We found a clear horizontal effect at spatial frequencies around 7.9 cpd against a 1/f noise background. At other spatial frequencies, horizontal thresholds were consistently higher than vertical thresholds, but there was no oblique effect (or inverse oblique effect) trend across all spatial frequencies. This separation of horizontal and oblique effects suggests that the two effects do not have a common origin. Instead, the implication is that at all spatial frequencies horizontal contrast is treated differently.
than vertical. There are undoubtedly good reasons for such an anisotropy in contrast perception, including the general anisotropy in scene contrast (Hansen & Essock, 2004), and also the fact that certain types of information are prevalent within the visual horizontal, including environmental features parallel with the gravitational horizontal and, in a recent example, content vital for face recognition (Dakin & Watt, 2009). Since both of these types of information would be expected to scale within the visual environment, being visible from any distance, they would not be expected to follow anything but a flat function of spatial frequency (as reported in Hansen & Essock, 2004).

The second anisotropy (poor sensitivity for vertical as well as horizontal) is seen here only at moderately high spatial frequencies (7.9 cpd). The observed numerical funcional bias in neural representation of orientation (Introduction) could be the basis of this second anisotropy.

Figure 11 presents evidence that a divisive gain control model of contrast masking (Equation 1) explains the change in threshold pattern across spatial frequency. At 7.9 cpd, there appears to be some ambiguity as to whether a subtractive or divisive process is more explanatory. Elsewhere (Essock et al., 2009), we have provided evidence that two processes may be responsible for producing the horizontal effect around 8 cpd—one an inverse oblique effect and the other a pronounced difference in horizontal–vertical masking. That previous finding is also apparent in Figure 6: a horizontal–vertical difference that is independent of spatial frequency which at 7.9 cpd is combined with an inverse oblique effect. We suspect that the presence of an explanatory ambiguity in the TvC functions measured at this spatial frequency may be related to the overlap of two distinct processes producing the prototypical horizontal effect anisotropy.

Relevance to real-world scene perception

These findings should be informative for use of 1/f noise as a stimulus in vision experiments (e.g., Geisler, Perry, & Najemnik, 2006; Kayser et al., 2006; Rajashekar et al., 2006; Tavassoli, van der Linde, Bovik, & Cormack, 2007). Whether or not these findings would hold true for ecologically coherent stimuli, i.e., photographs (Bex, Mareschal, & Dakin, 2007; Bex et al., 2009; Tolhurst & Tadmor, 1997), is an interesting question. An image of the world contains numerous oriented features, edges and contours and textures, and details at every scale. Our stimuli were intentionally defined as isotropic and broadband: they contain no oriented or scaled discontinuities or phase patterns, and it has been shown that the particular phase structure of natural scenes does affect the magnitude and perhaps the pattern of gain control effects (Bex et al., 2007; Hansen et al., 2003). However, some recent experiments using real-world imagery in tests of contrast sensitivity (Bex et al., 2009) have revealed masked CSFs similar to those obtained here. Thus, we again see a connection between contrast sensitivity in 1/f noise and contrast perception in real-world stimulation, emphasizing the relevance of measurable phenomena like the horizontal effect.

Appendix A

Contrast naming

Contrast values c cited in the text are calculated as the mean RMS (root-mean-square) contrast or standard deviation of stimulus pixel luminances [0,1] of all non-zero sectors included in a given stimulus and are presented on a decibel scale: 20*log10(c). So for example, a narrowband pedestal stimulus, as in Experiment 3, might have an RMS contrast c = 0.0245, which is referred to in text as a contrast of −32.2 dB. A broadband isotropic background image (as in Experiment 2) with RMS contrast 0.12 is made up of 24 sectors (see Methods) each with RMS contrast c = 0.0245; RMSbroad = √(24 × RMSsector). Hence, this broadband image is also given a contrast value of −32.2 dB.

This method of contrast naming is intended in part to recognize the narrowband nature of contrast perception: broadband contrast may be an accurate descriptor of the luminance distribution in a broadband image, but there is no reason to believe that it is used as a primary variable in spatial vision. It also allows for the assumption that, in the case where the target is narrowband and the mask is broadband, the non-target content has no effect on perception of the target; in other words, that only the local, target-like pedestal sector has an effect and that only its own local contrast should be considered. Likewise, it allows us to presume that the effects of all the other non-target sectors are independent of one another. In effect, we are considering our broadband stimulus to be a set of 24 separate narrowband stimuli rather than a single broadband stimulus.

This approach is beneficial to our data displays, particularly for Experiment 3. The abscissa is intended to be taken as representing the contrast of the target-matched pedestal content; hence, the values shown are accurate whether the background stimulus contains only the pedestal or the broadband noise stimulus. The table below translates between different contrast terms used in this paper. RMSbroad describes the (root-mean-square) contrast of a given broadband, isotropic 1/f noise pattern. RMSsector describes the contrast of the 1-octave, 45° “sectors” which combine to produce the broadband pattern. RMStarget describes the contrast of 1-octave, 45° triangle-weighted sectors used as target stimuli in these experiments. Data presented in this paper are in the form of Csector (for background images, whether broadband or
experiments, as described in Appendix A. In figures where the ordinate axis plotted contrast values, dB Ctarget was used, and when the abscissa plotted contrast, dB Csector was used.

Table A1. Contrast measures descriptive of the stimuli in these experiments, as described in Appendix A. In figures where the ordinate axis plotted contrast values, dB Ctarget was used, and when the abscissa plotted contrast, dB Csector was used.

<table>
<thead>
<tr>
<th></th>
<th>RMSbroa</th>
<th>RMSsector</th>
<th>RMStarget</th>
<th>dB Csector</th>
<th>dB Ctarget</th>
</tr>
</thead>
<tbody>
<tr>
<td>.0150</td>
<td>.0031</td>
<td>.0026</td>
<td>−50.3</td>
<td>−51.6</td>
<td></td>
</tr>
<tr>
<td>.0300</td>
<td>.0061</td>
<td>.0053</td>
<td>−44.3</td>
<td>−45.6</td>
<td></td>
</tr>
<tr>
<td>.0600</td>
<td>.0123</td>
<td>.0105</td>
<td>−38.2</td>
<td>−39.5</td>
<td></td>
</tr>
<tr>
<td>.1200</td>
<td>.0245</td>
<td>.0211</td>
<td>−32.2</td>
<td>−33.5</td>
<td></td>
</tr>
<tr>
<td>.1800</td>
<td>.0368</td>
<td>.0316</td>
<td>−28.7</td>
<td>−30.0</td>
<td></td>
</tr>
</tbody>
</table>

Appendix B

Curve Fitting

Experiment 3

In Experiment 3, Foley’s (1994) gain control model of contrast detection and discrimination was applied to both discrimination and detection-on-noise conditions. The model is defined generally as an internal response or $d'$ function, taking the following form:

$$d' = r \frac{c_i^{p+q}}{z^p + \sum_j w_j c_j^p},$$  \hspace{1cm} (B1)$$

where $R$, $z$, $p$, and $q$ are constants associated with the sensitive mechanism, $c_i$ is the contrast of stimulus components preferred by the mechanism, $c_j$ are all contrasts present in the stimulus including the preferred contrast, and $w_j$ are weights determining the extent to which other contrasts influence the mechanism. For our purposes, a simplified form of the model suffices, with $w_i$ set to 1, $c_m$ meant to represent the mean of all non-preferred contrasts in the stimulus, and $c_t$ identifying both target (sector) contrast and preferred stimulus components:

$$d' = r \frac{c_t^{p+q}}{z^p + w \cdot c_m^p + c_t^p}.$$  \hspace{1cm} (B2)$$

With this formulation, $c_t$ is taken to indicate the contrast of the target sector (including both background and test content), and $c_m$ indicates the contrast of a broadband mask as indicated in Appendix A. Threshold contrast is calculated by finding the change $c_\Delta$ in $c_t$ which will produce a predetermined change in the $d'$ level of 1.3 determined by the experimental method:

$$d' = r \frac{(c_t + c_\Delta)^{p+q}}{z^p + w \cdot c_m^p + (c_t + c_\Delta)^p} - r \frac{c_t^{p+q}}{z^p + w \cdot c_m^p + c_t^p}. \hspace{1cm} (B3)$$

Threshold data for each were fit to $c_\Delta$ values through a downhill simplex algorithm (Press, Teukolsky, Vetterling, & Flannery, 1988) allowing all parameters, e.g., $\phi = \{p, q, r, z, w\}$, to vary minimizing the chi-squared statistic between model and data:

$$\chi^2 = \frac{(c_\Delta(\phi) - c_{\text{data}})^2}{\sigma_{\text{data}}^2}. \hspace{1cm} (B4)$$

Experiment 2

Experiment 2 data do not constrain the parameters of such a model of contrast detection and discrimination and hence require a different approach to fitting. To estimate $w$ values for these data, reasonable values of $p = 2, q = 0.4$, and $r = 32$ were fixed for all subjects across all spatial frequencies and orientations (cf. Holmes & Meese, 2004; Legge & Foley, 1981). The $z$ values for five spatial frequencies and four orientations were reduced to just 5 parameters per observer, by making $z$ a function of the contrast threshold $c_\Delta$ (Yu et al., 2003), the inverse of a 4-parameter CSF function (Watson & Ahumada, 2005; Yang et al., 1995):

$$z = c_\Delta(r \cdot c^q + 1)^{\frac{1}{q}},$$  \hspace{1cm} (B5)$$

$$c_\Delta^{-1} = \frac{G \exp(f/f_0)}{1 + a \cdot (1 + f/f_1)^{-2}}.$$  \hspace{1cm} (B6)$$

Here, $f$ is stimulus spatial frequency, and $f_0$ and $f_1$, respectively, control rate of high and low spatial frequency attenuation. Since the oblique effect is known to appear only at higher spatial frequencies, we allowed $f_0$ to take on both a “cardinal” and an “oblique” value, so $z$ was fit with 5 parameters ($G, f_0, f_0, f_1$, and $a$).

Essentially, model application for Experiment 2 was a fit of two sensitivity parameters: $z$ and $w$. As described above, $z$ was assumed to follow a typical CSF shape. The masked sensitivity parameter, $w$, was fit with unique values at each spatial frequency and orientation.
Acknowledgments

Supported by Grant # N00014-03-1-0224 from the Office of Naval Research and Kentucky Space Grant Consortium – NASA.

Commercial relationships: none.
Corresponding author: Andrew M. Haun.
Email: andrew.haun@schepens.harvard.edu.
Address: Schepens Eye Research Institute, 20 Staniford Street, Boston, MA 02114-2500, USA.

References


