Some observations on the pedestal effect

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The pedestal or dipper effect is the large improvement in the detectability of a sinusoidal grating observed when it is added to a masking or pedestal grating of the same spatial frequency, orientation, and phase. We measured the pedestal effect in both broadband and notched noise—noise from which a 1.5-octave band centered on the signal frequency had been removed. Although the pedestal effect persists in broadband noise, it almost disappears in the notched noise. Furthermore, the pedestal effect is substantial when either high- or low-pass masking noise is used. We conclude that the pedestal effect in the absence of notched noise results principally from the use of information derived from channels with peak sensitivities at spatial frequencies different from that of the signal and the pedestal. We speculate that the spatial-frequency components of the notched noise above and below the spatial frequency of the signal and the pedestal prevent "off-frequency looking," that is, prevent the use of information about changes in contrast carried in channels tuned to spatial frequencies that are very much different from that of the signal and the pedestal. Thus, the pedestal or dipper effect measured without notched noise appears not to be a characteristic of individual spatial-frequency-tuned channels.

Keywords: contrast discrimination, off-frequency looking, contrast gain control, nonlinear transducer function, dipper effect, masking, spatial vision

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Introduction

Behavioral evidence from measurements of detection thresholds suggests that the early visual system is composed of many spatial-frequency-selective channels (Blakemore & Campbell, 1969; Campbell & Robson, 1968; DeValois & DeValois, 1988; Graham & Nachmias, 1971; Henning, 1988; Henning, Hertz, & Hinton, 1981). Although the notion of linear and independent channels is probably not viable (Albrecht & DeValois, 1981; Derrington & Henning, 1989; Henning, Hertz, & Broadbent, 1975; Wichmann, 2004; Wichmann & Tollin, 1997a, 1997b), the multichannel model still captures many crucial aspects of early spatial vision, and even in nonlinear systems, the determination of the linear component of the system typically remains important. However, it is the knowledge of the visual system's operation at suprathreshold contrasts that is a prerequisite for virtually any useful model of spatial vision.

Sinusoidal contrast discrimination provides one useful way to gain insight into the characterization of contrast transduction and the contrast gain control mechanisms thought to operate at suprathreshold contrasts within the single channels inferred from detection thresholds. It is hardly surprising, then, that sinusoidal contrast discrimination has been studied extensively since Nachmias and Sansbury's influential article in 1974 (Bradley & Ohzawa, 1986; Burton, 1981; Cannon & Fullenkamp, 1991; Dannemiller & Stephens, 1998; Foley, 1994; Foley & Boynton, 1993; Foley & Chen, 1997; Foley & Legge, 1981; Georgeson & Georgeson, 1987; Gorea & Sagi, 2001; Kontsevich, Chen, & Tyler, 2002; Legge, 1981; Legge & Foley, 1980; Legge, Kersten, & Burgess, 1987; Nachmias & Sansbury, 1974; Ross & Speed, 1991; Wichmann, 1999; Yang & Makous, 1995).

The most prominent finding of studies of sinusoidal contrast discrimination is the *dipper*-shaped threshold-versus-contrast (TvC) function in which the contrast of the signal or increment at "threshold" is plotted against pedestal contrast. In the case we consider, where the pedestal is a sinusoidal grating with the same spatial frequency, orientation, phase, and duration as the grating to be detected, the signal and increment contrasts are identical. For a limited range of low pedestal contrasts, contrast discrimination is possible with signal contrasts that are too small to be seen without the pedestal; this is the pedestal or "dipper" effect. In vision, three main explanations of the effect have been suggested: first, a nonlinear transducer (Foley & Legge, 1981; Legge, 1981; Legge & Foley, 1980; Yang & Makous, 1995), second, contrast gain control (Foley, 1994; Foley & Chen, 1997; Wichmann, 1999), and third, stimulus uncertainty (Pelli, 1985).

Amplitude discrimination in hearing is formally equivalent to contrast discrimination in vision, and indeed, a dipper-shaped "TvC" curve is also found in hearing. Models in hearing combine an energy transducer with a noise whose standard deviation is, in effect, proportional

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to the mean signal strength (Henning, 1967, 1969). Only very recently in vision has there been debate about whether, as in hearing, the internal sources of noise variance depend on signal strength (Gorea & Sagi, 2001; Henning, Bird, & Wichmann, 2002; Kontsevich et al., 2002; Wichmann, 1999). A further source of interest in hearing is the nature of the mechanisms underlying the dynamic range (10^6) over which amplitude discrimination (governed approximately by Weber's law) is possible (Plack & Viemeister, 1993; Viemeister, 1972; Zwicker, 1956, 1970). One of the mechanisms considered in hearing is off-frequency listening (Patterson, 1976; Zwicker, 1970)—by analogy, off-frequency looking (Henning et al., 1981; Losada & Mullen, 1995).

In this article, we use spectrally flat noise, no noise, and a flat noise from which a 1.5-octave notch centered on the signal frequency has been removed. We used a signal grating of 4 c/deg, and were our observers to base their discrimination solely on the output of a linear channel tuned to 4 c/deg, we would not expect any differences in the shape and the depth of the dipper (after normalization) between *any* of the three experimental conditions reported above. If we consider divisive contrast gain control mechanisms that integrate stimuli across a broad range of spatial frequencies (Carandini & Heeger, 1994; Carandini, Heeger, & Movshon, 1997; Heeger, 1992; Schwartz & Simoncelli, 2001), the dipper is predicted to be less pronounced in the broadband-noise condition than with no noise, as can be seen from, and as confirmed by, our data. However, for this class of model, a notch in the noise should result in a *release* from masking, that is, a dipper more closely resembling the no-noise condition. This is clearly not what our results will show.

Our experiments cast doubt on previous attempts to model the TvC curve that shows a big dipper effect in spatial vision as arising from characteristics of a single spatial-frequency-tuned channel. Rather, our experimental results with no noise and with broadband noise are consistent with the dipper's arising from off-frequency looking: As pedestal contrast increases, observers appear to shift the channel through which they perform the discrimination away from those tuned to the spatial frequency of the signal. Thus, the TvC curve attributable to the operation of a single channel is that derived from the notched-noise experiment. We base this conclusion on results from the three masking conditions with sinusoidal gratings where we have carefully manipulated the spectral properties of the masking noise.

Methods

Several two-alternative forced-choice detection and discrimination experiments were performed. On each trial of all the experiments, there were two 86-ms-long temporal intervals, separated by a 250-ms pause. The signal to be detected, a horizontally orientated sinusoidal grating, was present in one of the two observation intervals. The observers' task was to choose the interval in which the signal had been presented by pressing one of two keys. The probability of the signal's being in the first interval was 0.5 on every trial. The contrast of the signal was fixed for blocks of 50 trials and then changed to determine four to eight points on the psychometric function relating the proportion of correct responses to signal contrast. The experiments were then repeated in a different order to obtain at least 500 observations per psychometric function for each observer. (In preliminary detection experiments, 100 observations per point were only obtained at two points immediately above and below the value corresponding to 75% correct to speed up exploration with the more experienced observer.) Including training, the results reported in this study are based on 65,650 trials for observer N.A.L., 23,335 for observer T.C.C., and 28,765 for observer G.B.H., who is one of the authors.

Different types of masking stimuli were presented in both observation intervals. One type of masking stimulus consisted of a sinusoid of the same orientation, spatial frequency, phase, and duration as the signal. The contrast of this masker, or pedestal as such a masker is sometimes called, was fixed, and 50-observation-per-point psychometric functions were obtained by varying the signal contrast. Then, the pedestal contrast was changed and the process was repeated for pedestal contrasts increasing from 0% to 32%. The process was repeated with decreasing pedestal contrast so that, in the end, psychometric functions with at least 500 observations were obtained. The observers' task was to choose the observation interval in which the signal had been added to the pedestal. Because the pedestal had the same spatial frequency, duration, orientation, and phase as the signal, the task became one of contrast discrimination. Only a 4-c/deg sinusoidal signal was used for this experiment.

A second type of masker consisted of one-dimensional Gaussian noise of the same (horizontal) orientation as the signal. The noise, when it was used, was presented in both observation intervals for the same 86-ms duration as the signal, and the observers' task was again to indicate the interval in which the sinusoidal signal was present. In some experiments, both the sinusoidal masker (pedestal) and the noise masker were used.

The stimuli were generated digitally and displayed carefully linearized displays, either on monochrome Clinton Monoray CRT displays—modified Richardson Electronics MR2000HB-MED CRT's with fast DP104 phosphor—(observers T.C.C. and G.B.H.) or on a Sony GDM-520 in monochrome mode (observer N.A.L.) using Cambridge Research Systems VSG 2/5 cards. Identical systems in Oxford and Tübingen were used. The stimuli were produced using a two-field frame (75-Hz frame rate for the Clinton displays, 70-Hz frame rate for the Sony display) with the masking noise, when present, produced in alternate fields. The signal, in the observation interval in which it was presented, as well as the pedestal, when present, was produced in the other field. In the nonsignal interval, and when neither masking noise nor pedestal was present, uniform fields replaced the signal, the noise, or the pedestal appropriately. The addition of neither the signal, nor the pedestal, nor the noise had any effect on the approximately 50 cd/m^2 mean luminance of the displays. The signal and the two masker types were all presented inside a common circularly symmetrical spatial Hanning window, the diameter of which subtended 6° of visual angle at the viewing distance of 1.6 m; the 86-ms temporal window was rectangular.

The first preliminary experiment measured contrast sensitivity as a function of the spatial frequency of the signal without any sinusoidal masker (pedestal) and was repeated in two noise conditions—one in which the noise-power density spectrum was flat to an 42.7-c/deg upper bound and one in which a nominal 2-octave notch centered geometrically on 4 c/deg was produced by adding a spectrally flat noise that had been low-pass filtered to remove components nominally above 2 c/deg to the same noise that had been high-pass filtered to remove components nominally below 8 c/deg. Filtering was performed in the frequency domain, and the noises then transformed to the space domain, suitably windowed (Rabiner & Gold, 1975), and rounded to the 8-bit dynamic range of our video memory (VRAM). Because of the finite dynamic range of the visual display system and the finite size of the stimuli, generation of notched noises is not trivial. In particular, Gaussian noise samples inevitably call for luminance values that exceed the dynamic range of the display system. Truncation at the boundaries of the dynamic range leads to clipping, which, if excessive, removes the notch. Reducing noise power reduces the amount of clipping but leaves both a less effective masker and fewer bits with which to represent the details of the filtered noise on which the characteristics of the notch depend. We generated a large number of noise samples and only kept those that had the following:

1. A suitably high noise-power density with a mean value (across the ensemble) equivalent to a Michelson contrast of approximately 3.4% at each spatial frequency in the discrete representation of the noise spectrum—the broadband noise with this mean spectral density raises the detection threshold for a 4-c/deg grating by a factor of about 8.
2. A suitably deep notch; the notched noises we kept had a width of at least 1.5 octaves and effectively lacked components between 2.67 and 7.5 c/deg.
3. An attenuation in the notch that was at least 35 dB below the noise power on either side of the notch.
4. A flat noise-power density spectrum in most of the passbands above and below the notch.

Figure 1 shows the noise-power density averaged over the 100 noises we used. The figure shows the spectrum after windowing and rounding. The standard deviation over the noise samples at each spatial frequency was below 5 dB. All stimuli were generated as 512 × 512 pixel arrays, which, at the viewing distance of 1.6 m, gave the diameter of the Hanning window within which the stimuli were viewed an angular subtense of 6.0°.

Figure 2 illustrates the stimuli. The upper panels show noises—the notched noise on the left and the broadband noise on the right. The middle panels are both copies of

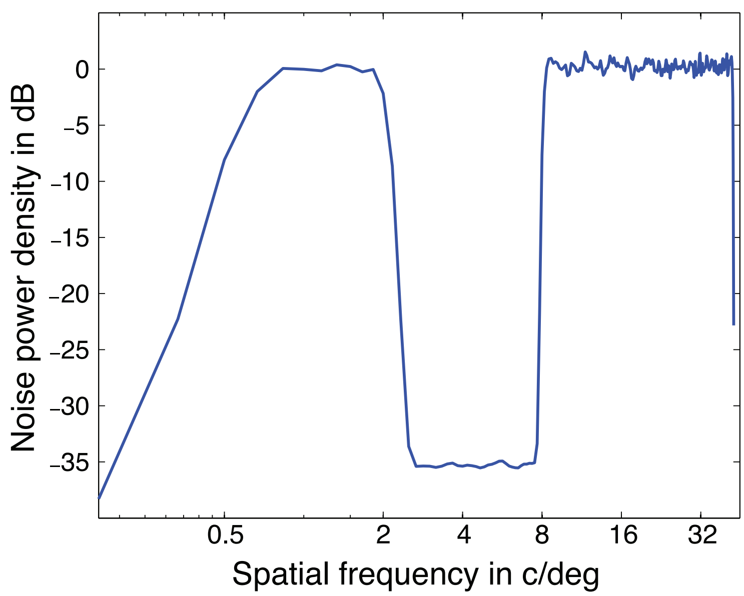

Figure 1. The curve shows average noise-power density (in decibels; mean level corresponding to a Michelson contrast of 3.4% for each component in the discrete representation of the noise spectrum) as a function of spatial frequency (logarithmic scale). The data are for 100 notched noises with the notch centered geometrically on 4 c/deg. The noise-power density in the stop band of the notch is at least 35 dB below that in the passbands.

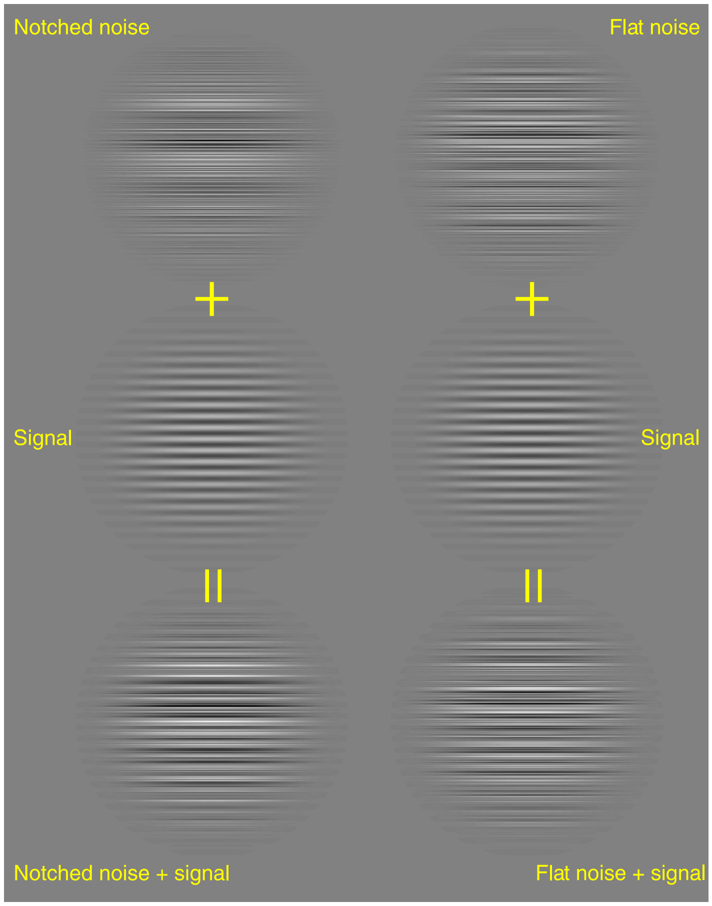

Figure 2. The top panels illustrate notched noise (left) and broadband noise (right). The center panels illustrate the 4-c/deg sinusoidal signal, and the bottom panels show the result when the signal is added to the noise.

the sinusoidal grating to be detected, and the bottom panels show the sums of the signal and noises. The signal in the notched noise is more clearly visible than that in the broadband noise.

Preliminary experiments

In preliminary experiments, we measured the contrast sensitivity of sinusoidal gratings for spatial frequencies ranging from 1 to 12 c/deg both with no masking noise and then with both the broadband and notched-noise maskers.

We also measured the effect of the addition of a sinusoidal masker (pedestal) with contrasts ranging from 0% to 32% on the detectability of a 4-c/deg sinusoidal signal both with and without the broadband-noise masker.

Results and discussion

The results of the preliminary detection experiment with three different masking noises and no pedestal are shown for one observer, G.B.H., in Figure 3. The figure shows the contrast corresponding to 75% correct responses as a function of spatial frequency, and both axes are logarithmic. The filled circles show the results obtained in the no-noise condition; the downward-pointing triangles indicate the results obtained with the spectrally flat noise; the stars show the results obtained with the notched noise, the geometrical center of which is indicated by the extended vertical red line. The error bars, where shown and when larger than the symbols, indicate a range of approximately ±1 *SD* obtained by a bootstrap method from cumulative Gaussian fits to the underlying psychometric functions (Wichmann & Hill, 2001a, 2001b). Similar results were obtained from the other observers.

First, consider the results in the condition with no masking noise (circles). The reciprocal of the thresholds in this condition is just the standard contrast-sensitivity function (CSF). Because the underlying psychometric functions are roughly parallel on semilogarithmic coordinates, the shape of the CSF does not depend much on the performance level chosen for the threshold. Here, we use the conventional 75% correct level. The results are similar to those obtained with other observers using stimuli of duration similar to our 86-ms stimuli (Bird, Henning, & Wichmann, 2002; Kelly, 1979a, 1979b; Robson, 1966). Performance, except

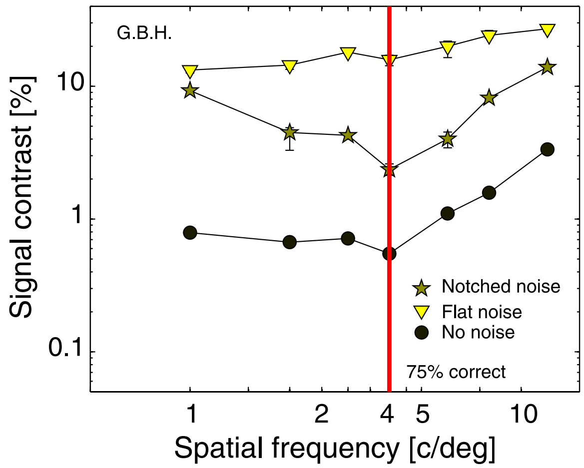

Figure 3. The data show the signal contrast at 75% correct responses as a function of spatial frequency for G.B.H. Both axes are logarithmic. Stars show performance in the notched noise—a 1.5-octave-wide notch centered on 4 c/deg. Circles show performance in the absence of masking noise, whereas downward-pointing triangles indicate performance in the presence of the broadband masking noise. Error bars, where visible, show estimates of ±1 *SD*.

possibly at the lowest spatial frequency, is a roughly monotonic decreasing function of spatial frequency.

When spectrally flat broadband masking noise is added (triangles), contrast sensitivity is lower by at least a factor of 8 across all three observers and depends much less on spatial frequency. The flat noise produces considerable masking at all the spatial frequencies we used. With the broadband noise, there is some loss in sensitivity with increasing spatial frequency, but the noise has a flat spectrum. The increase in masking is probably a result of the increasing bandwidth (approximately ±1 octave) of the spatial-frequency-tuned channels through which the signals are thought to be detected (Blakemore & Campbell, 1969; Campbell & Robson, 1968; DeValois & DeValois, 1988; Graham & Nachmias, 1971; Henning, 1988; Henning et al., 1981; Stromeyer & Julesz, 1972). Increases in bandwidth that were exactly proportional to frequency would result in increases in masking (measured by the contrast of the signal at 75% correct) at a rate of 1 log unit per decade of spatial frequency—not far from the slope of 0.9 log units per decade that we observe if the lowest spatial frequency is excluded (approximately constant masking across spatial frequency may be obtained with "pink" noise, see Henning et al., 2002).

The amount of masking (logarithmic units) is shown by the difference between the circles and the other symbols. The amount of masking produced by the notched noise (stars) and by the broadband noise (triangles) is similar only at the very low and very high spatial frequencies as might be expected. The least masking produced by the notched noise occurs in the center of the notch near 4 c/deg—about 0.4 log units of masking for the notched noise compared with 0.9 log units for all the observers with the broadband noise. With the notched noise, the amount of masking increases as the spatial frequency of the signal falls either below or above 4 c/deg, but there is a visible difference until the signal frequency is about an octave above or below the center of the notch.

These results are not inconsistent with some measurements of the shape of the spatial-frequency-tuned "channels" through which the signals are assumed to be detected (Blakemore & Campbell, 1969; Campbell & Robson, 1968; DeValois & DeValois, 1988; Graham & Nachmias, 1971; Henning, 1988; Henning et al., 1981; Stromeyer & Julesz, 1972). Behavioral measurements of channel shape using masking techniques suggest an asymmetric characteristic with the channel skirts falling about 0.7 log units per octave below the spatial frequency to which the channel responds best and only about 0.4 log units per octave above that frequency (Henning et al., 1981; Stromeyer & Julesz, 1972). Thus, it is the noise with spatial-frequency components that are within an octave or so of the signal frequency that has measurable effects on the detectability of the signal. The notch in our noise is approximately 1.5 octaves wide, but the 4-c/deg channel is so broad that there is some masking from the components of the noise that are more than an octave away.

Figure 4 shows the signal contrast at 60%, 75%, and 90% correct as a function of the pedestal contrast in the absence of any added masking noise for the three observers. The performance levels are determined by fitting Gumbel functions to the psychometric functions that relate the proportion of correct responses to the logarithm of signal contrast and then converting the log thresholds back to contrasts (Wichmann & Hill, 2001a, 2001b). Both axes are logarithmic. An indication of the slope of the psychometric functions (and, hence, the variability around each data point) can be obtained from the vertical separation of the contours at each pedestal level, but the error bars again show approximately ±1 *SD*. The results for the observers take the usual form (Bird et al., 2002; Bradley & Ohzawa, 1986; Cannon & Fullenkamp, 1991; Dannemiller & Stephens, 1998; Foley, 1994; Foley & Boynton, 1993; Foley & Chen, 1997; Foley & Legge, 1981; Georgeson & Georgeson, 1987; Gorea & Sagi, 2001; Kontsevich et al., 2002; Legge, 1981; Legge & Foley, 1980; Legge et al., 1987; Wichmann, 1999; Yang & Makous, 1995): As the pedestal contrast increases from zero, performance improves until the pedestal contrast is about twice (90% correct) or 10 times (60% correct) that of the corresponding threshold and then deteriorates in a way that corresponds roughly to Weber's law (Bird et al., 2002; Wichmann, 1999). The form of the curves is sometimes called the dipper function (Foley, 1994; Foley & Legge, 1981; Georgeson & Georgeson, 1987; Legge & Foley, 1980), but the shape depends on the performance level that determines the contour (Bird et al., 2002; Wichmann, 1999). The improvement is much greater for the 60% contour than for the 90% contour, which implies shallower psychometric functions in

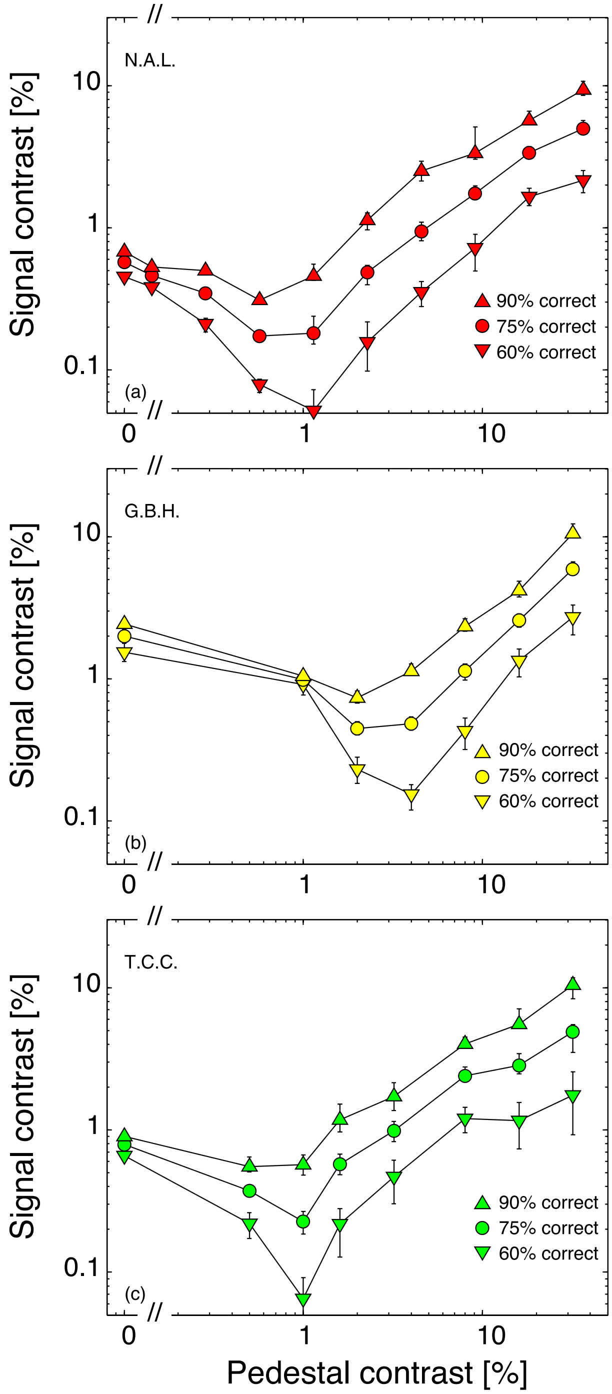

Figure 4. The data show signal contrast as a function of pedestal contrast for N.A.L. (a), G.B.H. (b), and T.C.C. (c). Both axes are logarithmic, and contours corresponding to 90%, 75%, and 60% correct responses are shown. Detection data obtained in the absence of a pedestal are shown at the extreme left end for comparison (pedestal contrast = 0). Error bars, where visible, show estimates of ±1 *SD*.

the vicinity of the best performance. The shallower slope is sometimes taken to indicate that it is the reduction in signal uncertainty due to the presence of the pedestal that causes the improved performance (Pelli, 1985).

The results of the preliminary experiments serve to illustrate the usual form of the dipper or pedestal effect with our observers and stimulus parameters (Figure 4). They also indicate the way in which contrast sensitivity depends on spatial frequency both with and without broadband, flat Gaussian masking noise and in the presence of the notched noise (Figure 3).

We now wish to measure the pedestal effect when the signal (as well as pedestal) is presented at 4 c/deg in a notched noise with the notch centered on that spatial frequency.

Main experiment: Results and discussion

Figures 5, 6, and 7 show, separately for each observer, signal contrast as a function of pedestal contrast at each of three performance levels: 60% in the top panels, 75% in the center panels, and 90% in the bottom panels. Each panel shows three curves: (1) the curve for broadband masking noise (downward-pointing triangles), (2) the curve for the notched masking noise (stars), and (3) the curve for the absence of masking noise (circles). Figure 5 shows the results for observer G.B.H. that were obtained when the noise-power density in the passbands was the same. The masking is so large with the broadband noise that the dipper effect is shifted to such high contrasts as to be almost obscured because sufficient pedestal contrast cannot be produced to generate the rising part of the TvC function. (As signal and pedestal are interleaved with the noise, the signal plus pedestal are limited to a maximum of 50% contrast.) A clearer picture emerges in Figures 6 and 7 for the other observers. To generate these data, we scaled down the noise-power density for the broadband noise to produce the same amount of masking for the 4-c/deg signal at the 75% level as is produced by the notched noise at the same spatial frequency. Under these conditions, the small dipper effect with broadband noise is clearly larger than that with the notched noise.

To compare the shape of the functions closely, we show in Figures 8, 9, and 10, again separately for each observer, normalized signal contrast as a function of normalized pedestal contrast. The signal and the pedestal contrasts for all three curves in all three panels of Figures 8, 9, and 10 have been normalized by the threshold contrast obtained in the absence of a pedestal (data shown at the extreme left end of all three panels of the figures). The signal frequency was 4 c/deg, and both axes are logarithmic. Contours for 60%, 75%, and 90% correct responses are shown in separate panels of each figure. This procedure, with a pedestal contrast of zero, sets the normalized signal contrast at threshold to one.

Inspection of any set of figures shows that data from the notched-noise condition are different in that the pedestal

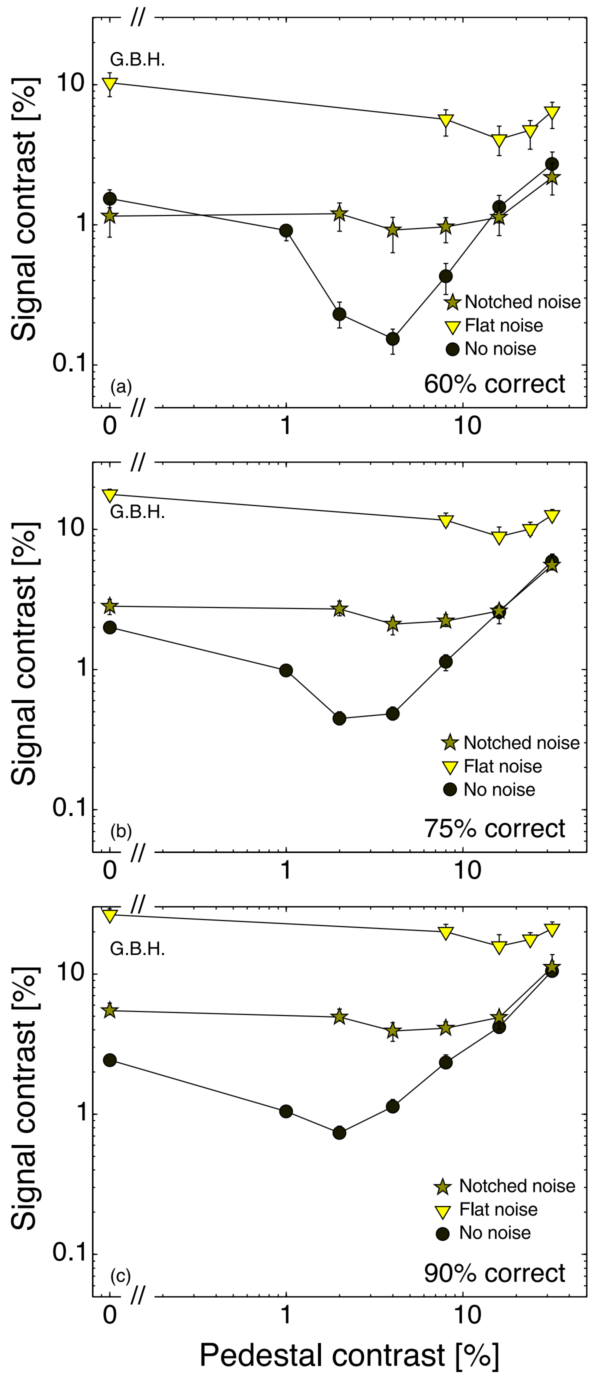

Figure 5. Each panel shows signal contrast for observer G.B.H. as a function of pedestal contrast on double logarithmic coordinates. Contours corresponding to 60% correct, 75% correct, and 90% correct are shown in Panels a–c, respectively. Circles show results obtained with no masking noise (replotted from Figure 4). Downward-pointing triangles show results obtained with broadband masking noise at a noise-power density that was the maximum attainable on our display system; that is, both notched noise and broadband noise had the same noise-power density below 4 c/deg and above 16 c/deg. Stars indicate the results obtained with the notched noise. Detection data obtained in the absence of a pedestal (pedestal contrast = 0) are shown at the extreme left end for comparison. Error bars, where visible, show estimates of ±1 *SD*.

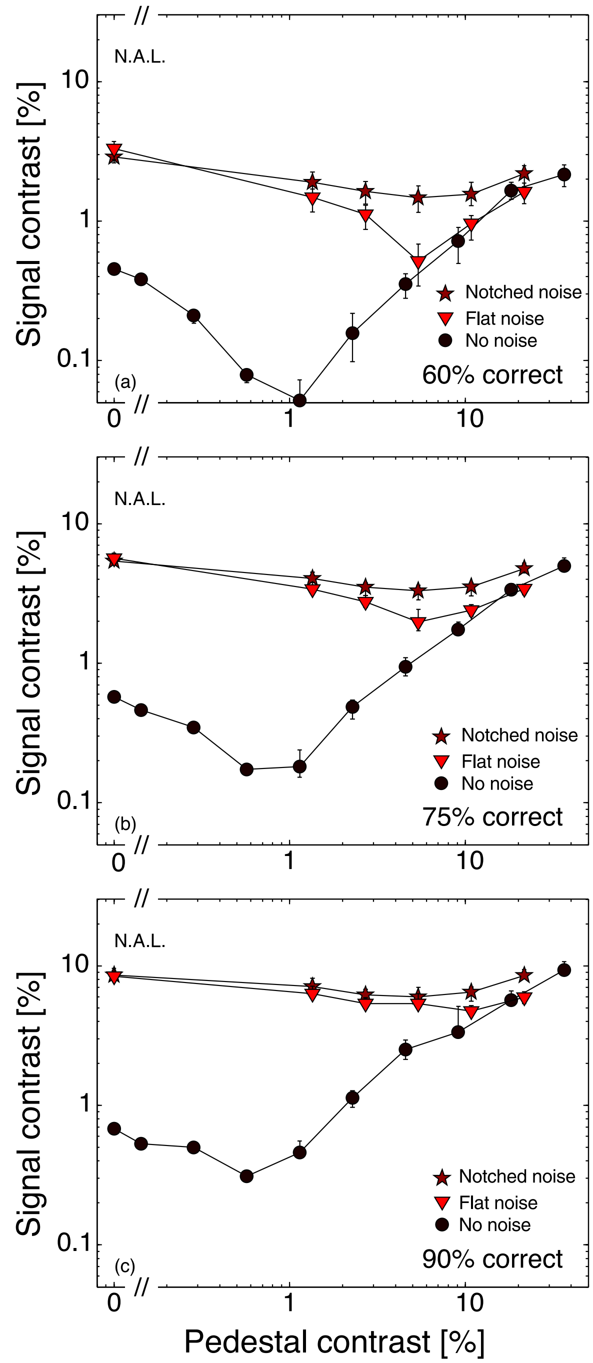

Figure 6. Same as Figure 5 except that this figure shows the results for observer N.A.L. and that the spectrum level of the broadband masking noise was adjusted to produce similar masking in detection (no pedestal) to that of the notched noise at 4 c/deg.

effect is very much reduced at every performance level. For observer G.B.H., for example, when the notched-noise condition is compared with the no-noise condition at the 60% performance level where the pedestal effect is greatest, we find that the 1.0 log unit improvement in detectability is reduced to a 0.3 log unit improvement (a factor of 5.00 less enhancement); for the 75% correct

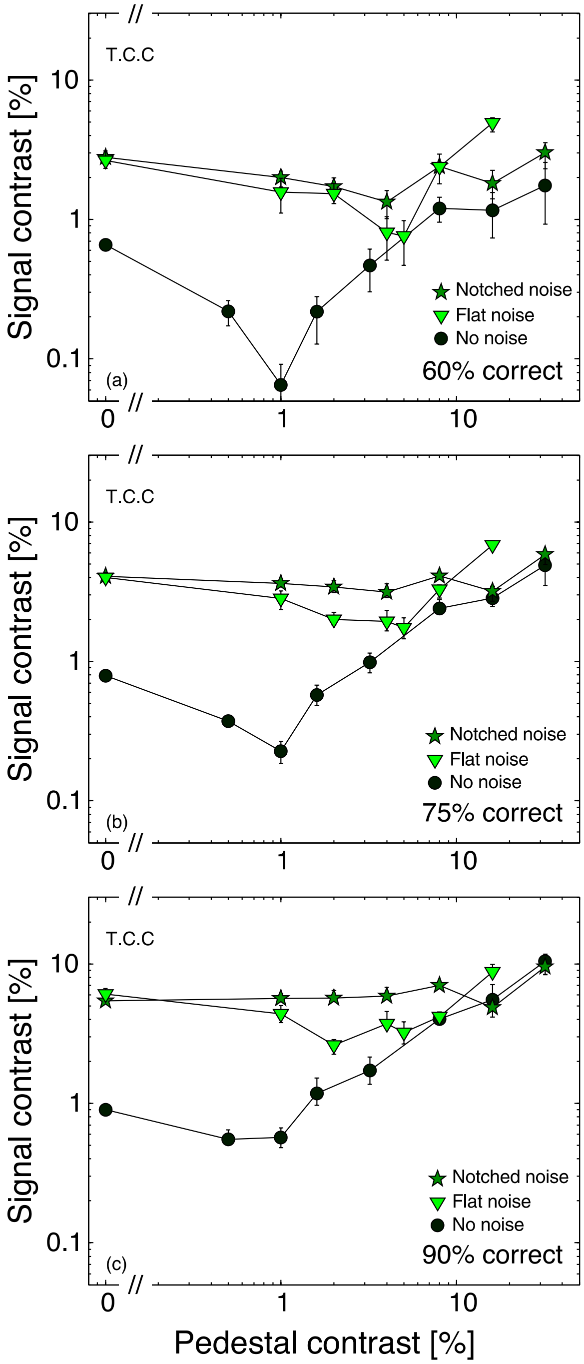

Figure 7. Same as Figure 6 except that this figure shows the results for observer T.C.C.

level, the improvement drops from 0.70 to 0.19 log units (a factor of 3.25 less enhancement); at 90%, the improvement drops from 0.55 to 0.09 log units (a factor of 2.86 less enhancement). Similarly, when the notched-noise condition is compared with the broadband-noise condition, we find that the depth of the dipper is reduced by a factor of 1.33 (at 90% correct) to 2.00 (at 60% correct).

Were our observers to base their discrimination solely on the output of a linear channel tuned to 4 c/deg, we would not expect any differences in the shape and the depth of the dipper (after normalization) between *any* of the three experimental conditions reported above.

If we allowed for divisive contrast gain control mechanisms that integrate stimuli across a broad range of spatial frequencies (Carandini & Heeger, 1994;

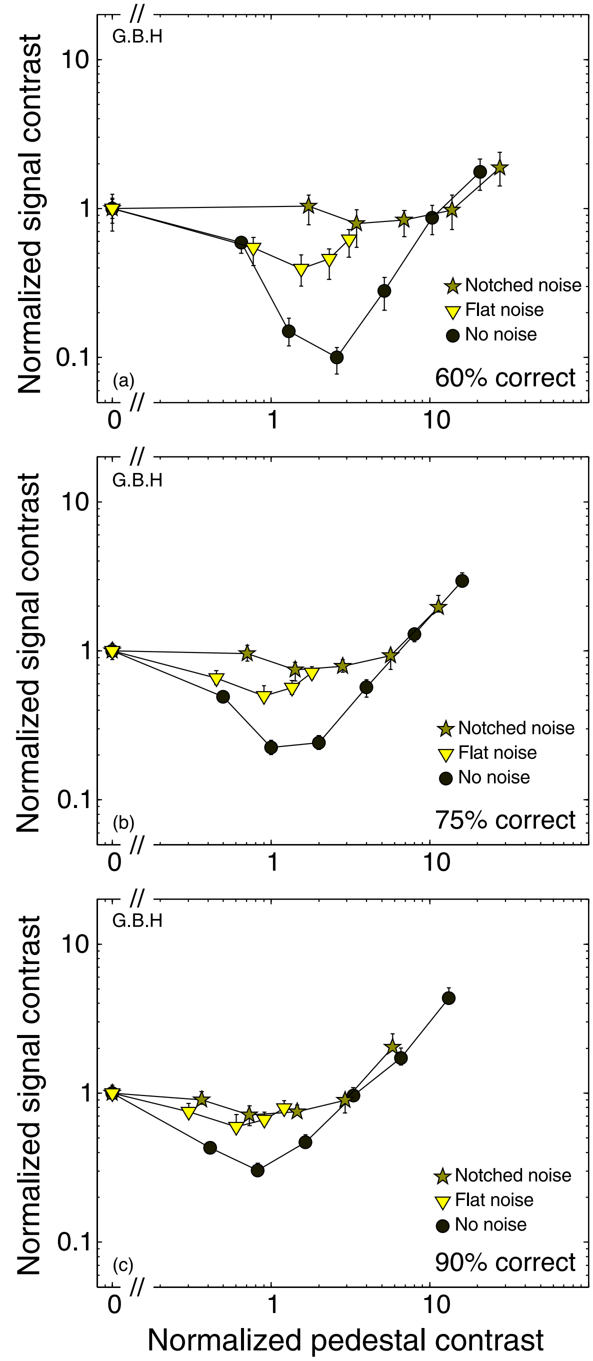

Figure 8. Each panel shows normalized signal contrast for G.B.H. as a function of normalized pedestal contrast on double logarithmic coordinates. Contours corresponding to 60% correct, 75% correct, and 90% correct are shown in Panels a–c, respectively. The data are from Figure 5.

channels tuned to spatial frequencies other than that of the signal are unlikely to contribute much to the overall performance.

In pedestal experiments, however, the assumption that a single channel determines the observer's behavior is more difficult to justify. As the pedestal contrast increases, the response of the neurons underlying the channel tuned to the spatial frequency of the signal has driven up their response function toward saturation (DeValois & DeValois, 1988; Geisler & Albrecht, 1997b; Geisler, Albrecht, Salvi, & Saunders, 1991; Henning, 2004). In addition, good discrimination performance hinges on the neural response that rests on the steep part of the function relating rate and contrast. Under these conditions, moving to a channel that will respond to the signal (and pedestal) frequency but does not respond best to that frequency might have the advantage of lowering the neural response rate to a steeper part of the function and, thus, improving discrimination performance. This is called "off-frequency" looking.

Off-frequency looking would be of little benefit when the pedestal level is very high—because the output of all the relatively broadly tuned channels would be driven up above their optimal operating point and because even at moderate pedestal levels, the outputs of the channels appear to become highly correlated (Henning et al., 2002)—or very low—because at low levels, the channels that are not tuned to the signal frequency would be responding, if at all, well below their optimal operating point. Thus, there is only a limited range of pedestal contrast over which off-frequency looking could improve performance. A further consequence of off-frequency looking stems from the fact that there is a sizeable range of contrasts—the central, approximately linear range of the rate versus contrast functions—over which good discrimination performance is possible (Geisler & Albrecht, 1997b). This means that over a range of pedestal contrasts, performance can be improved by combining information from different channels. It seems likely that it is the combination of information from different channels that produces the usual dipper or pedestal effect.

Using information from off-frequency channels would increase the range of pedestal levels over which good discrimination performance is possible. As the pedestal level increases, the observers should continue to use information from channels with peak sensitivities that are farther and farther from the signal frequency until, ultimately, they run out of channels. Discrimination performance would then deteriorate in a fashion determined, presumably, by the characteristics of last spatial-frequency channel in use or because with increasing pedestal levels, probability summation becomes weak because of increasing correlation among the channels' output (Bird et al., 2002). One consequence of such a procedure is that the dipper functions for signals at all spatial frequencies should ultimately coincide as pedestal levels increase. That is what is found (Bird et al., 2002; Bradley & Ohzawa, 1986).

The effect of the notched noise is to limit the number of spatial-frequency-tuned channels that can be of use to the observers in discriminating the interval containing the signal plus pedestal from the pedestal alone. The dipper or pedestal effect does not disappear when the observers perform the discrimination task in a notched noise, but the magnitude of the improvement is less by a factor of between 2.86 and 5.00 depending on the performance contour being considered. Further, the range of pedestal contrasts over which "subthreshold" performance occurs is greatly reduced in the notched noise. Inspection of Panels a of Figures 5 to 10—the 60% contours—for example, shows that the range of pedestal contrasts over which subthreshold performance occurs is very much reduced in the notched-noise condition. That the pedestal effect does not completely disappear in the notched-noise condition may be because of the following: our 1.5-octave notch permits some, albeit limited, off-frequency looking; there is some off-orientation looking within the notch; or there is a small pedestal effect within a single channel (Geisler & Albrecht, 1997b; Geisler et al., 1991). If the latter is true, then it is the very small pedestal effect seen in the presence of notched noise that models of contrast gain control (Heeger, 1992, 1994; Geisler & Albrecht, 1992, 1995, 1997a; Yang & Makous, 1995) need to fit rather than the large pedestal effects seen in the absence of noise.

One obvious implication of the above analysis is that the pedestal effect, which virtually disappears in notched noise, should return if the masking noise either only below or only above the signal frequency is removed because, in either case, off-frequency looking becomes possible. We tested this prediction in a supplementary experiment using either high- or low-pass noise.

In the supplementary experiment, the experimental conditions were as described in the Methods section save that masking noise was changed. For the low-pass case, the components of the broadband noise above the 4-c/deg signal frequency were removed, and for the high-pass case, the components below 4 c/deg were removed. In both cases, the noise-power density in the passband again had a Michelson contrast of 3.4% at each spatial frequency, and two of the previous observers participated in the experiment.

Figure 11 shows the results with low-pass noise separately for the two observers in the same format as Figure 3—signal contrast corresponding to 60%, 75%, and 90% correct responses is shown as a function of pedestal contrast. There is a clear dipper effect for both observers. The magnitude of the dip is lesser with no noise but is larger with the notch. The average drop at 60% is 3.5; at 75%, it is 2.2; and at 90%, it is 1.65. This compares to the average drop in the notched noise of 1.6, 1.5, and 1.3 at 60%, 75%, and 90%, respectively.

Figure 12 shows a similar result with high-pass noise. Here, the average drop in the dip is 3.6, 2.2, and 1.6 at

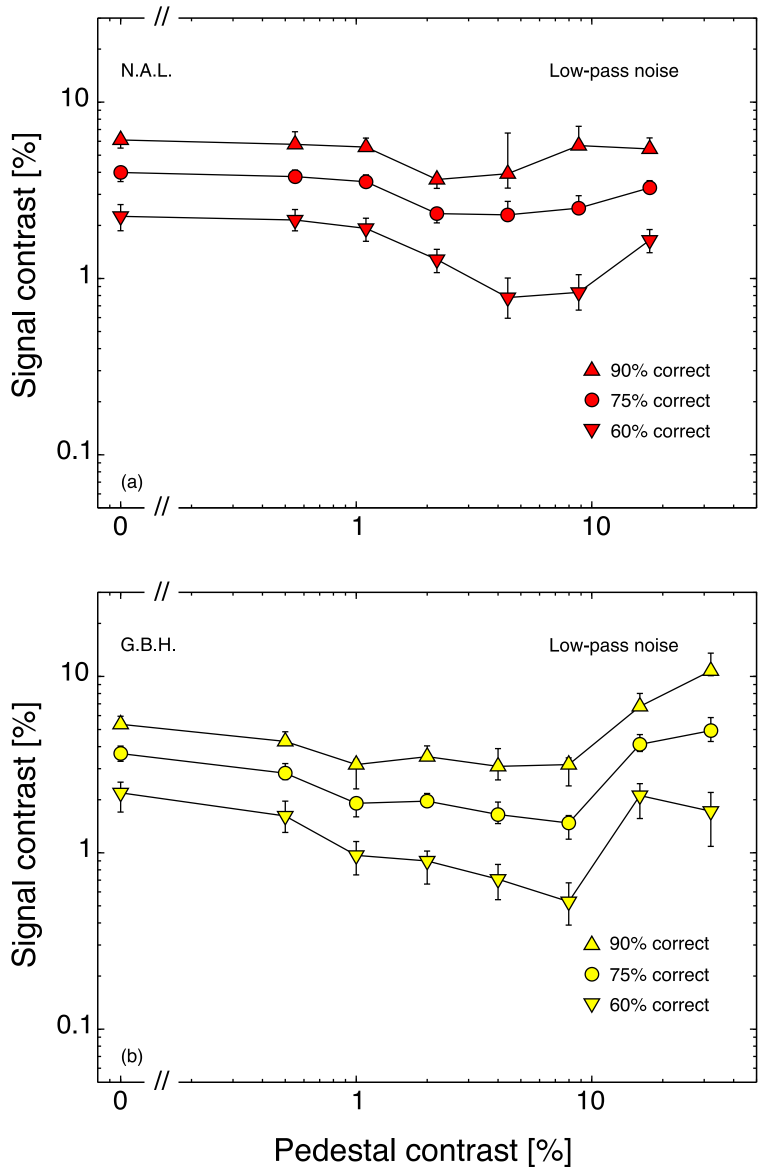

Figure 11. The panels show separately for each observer the signal contrast as a function of the pedestal contrast in the presence of low-pass noise with a 4-c/deg cutoff. Both axes are logarithmic, and contours corresponding to 60%, 75%, and 90% correct responses are shown. Detection data obtained in the absence of a pedestal are shown at the extreme left end for comparison (pedestal contrast = 0). Error bars, where visible, show estimates of ±1 *SD*.

60%, 75%, and 90%, respectively. Thus, the dipper-shaped TvC reappears. That the dip occurs at higher pedestal contrasts in high-pass noise is also consistent with the loss of peak sensitivity of channels tuned to higher spatial frequencies. Both results are consistent with the notion of off-frequency looking because in both cases, removing part of the noise allows useful off-frequency looking in parts of the spatial-frequency spectrum.

One final consideration is the number of independent, different, and equally sensitive spatial-frequency channels that would need to be combined to produce the biggest improvement in performance. Such a number is, of course, only a crude indicator because the calculation hinges on the channels being equally sensitive and uncorrelated, and the extent to which the channels are correlated is not clear (Henning et al., 2002, 1975). It is also difficult to estimate z values at low-performance levels. Nonetheless, the numbers are of some interest. To determine the number of independent channels that would be needed to move performance at its best in the notched-noise condition to its best in the no-noise condition, we use the 75% contour in the no-noise condition and note the z value associated with the corresponding signal contrast in the notched-noise condition. The ratio of the z values is then an estimate of the square root of the number of independent channels needed to move performance from that in the

Geisler, W. S., & Albrecht, D. G. (1997b). Visual cortex neurons in monkeys and cats: Detection, discrimination, and identification. *Visual Neuroscience, 14,* 897–919. [PubMed]

Geisler, W. S., Albrecht, D. G., Salvi, R. J., & Saunders, S. S. (1991). Discrimination performance of single neurons: Rate and temporal-pattern information. *Journal of Neurophysiology, 66,* 334–362. [PubMed]

Georgeson, M. A., & Georgeson, J. M. (1987). Facilitation and masking of briefly presented gratings: Time-course and contrast dependence. *Vision Research, 27,* 369–379. [PubMed]

Gorea, A., & Sagi, D. (2001). Disentangling signal from noise in visual contrast discrimination. *Nature Neuroscience, 4,* 1146–1150. [PubMed] [Article]

Graham, N., & Nachmias, J. (1971). Detection of grating patterns containing two spatial frequencies: A comparison of single channel and multichannel models. *Vision Research, 11,* 251–259. [PubMed]

Heeger, D. J. (1992). Normalization of cell responses in cat striate cortex. *Visual Neuroscience, 9,* 181–197. [PubMed]

Heeger, D. J. (1994). The representation of visual stimuli in primary visual cortex. *Current Directions in Psychological Science, 3,* 159–163.

Henning, G. B. (1967). A model for auditory discrimination and detection. *Journal of the Acoustical Society of America, 42,* 1325–1334. [PubMed]

Henning, G. B. (1969). Amplitude discrimination in noise, pedestal experiments, and additivity of masking. *Journal of the Acoustical Society of America, 45,* 426–435. [PubMed]

Henning, G. B. (1988). Spatial-frequency tuning as a function of temporal frequency and stimulus motion. *Journal of the Optical Society of America A, Optics and Image Science, 5,* 1362–1373. [PubMed]

Henning, G. B. (2004). Masking effects of low-frequency sinusoidal gratings on the detection of contrast modulation in high-frequency carriers. *Journal of the Optical Society of America A, Optics, Image Science, and Vision, 21,* 486–490. [PubMed]

Henning, G. B., Bird, C. M., & Wichmann, F. A. (2002). Contrast discrimination with pulse trains in pink noise. *Journal of the Optical Society of America A, Optics, Image Science, and Vision, 19,* 1259–1266. [PubMed]

Henning, G. B., Hertz, B. G., & Broadbent, D. E. (1975). Some experiments bearing on the hypothesis that the visual system analyzes patterns in independent bands of spatial frequency. *Vision Research, 15,* 887–897. [PubMed]

Henning, G. B., Hertz, B. G., & Hinton, J. L., (1981). Effects of different hypothetical detection mechanisms on the shape of spatial-frequency filters inferred from masking experiments: I. Noise masks. *Journal of the Optical Society of America, 71,* 574–581. [PubMed]

Kelly, D. H. (1979a). Motion and vision: I. Stabilized images of stationary gratings. *Journal of the Optical Society of America, 69,* 1266–1274. [PubMed]

Kelly, D. H. (1979b). Motion and vision: II. Stabilized spatio-temporal threshold surface. *Journal of the Optical Society of America, 69,* 1340–1349. [PubMed]

Kontsevich, L. L., Chen, C. C., & Tyler, C. W. (2002). Separating the effects of response nonlinearity and internal noise psychophysically. *Vision Research, 42,* 1771–1784. [PubMed]

Legge, G. E. (1981). A power law for contrast discrimination. *Vision Research, 21,* 457–467. [PubMed]

Legge, G. E., & Foley, J. M. (1980). Contrast masking in human vision. *Journal of the Optical Society of America, 70,* 1458–1471. [PubMed]

Legge, G. E., Kersten, D., & Burgess, A. E. (1987). Contrast discrimination in noise. *Journal of the Optical Society of America A, Optics and Image Science, 4,* 391–404. [PubMed]

Losada, M. A., & Mullen, K. T. (1995). Color and luminance spatial tuning estimated by noise masking in the absence of off-frequency looking. *Journal of the Optical Society of America A, Optics, Image Science, and Vision, 12,* 250–260. [PubMed]

Nachmias, J., & Sansbury, R. V. (1974). Grating contrast: Discrimination may be better than detection. *Vision Research, 14,* 1039–1042. [PubMed]

Patterson, R. D. (1976). Auditory filter shape derived with noise stimuli. *The Journal of the Acoustical Society of America, 59,* 640–654. [PubMed]

Pelli, D. G. (1985). Uncertainty explains many aspects of visual contrast detection and discrimination. *Journal of the Optical Society of America A, Optics and Image Science, 2,* 1508–1532. [PubMed]

Plack, C. J., & Viemeister, N. F. (1993). Suppression and the dynamic range of hearing. *Journal of the Acoustical Society of America, 93,* 976–982. [PubMed]

Rabiner, L., & Gold, B. (1975). *Theory and application of digital signal processing*. New York: Prentice-Hall International.

Robson, J. G. (1966). Spatial and temporal contrast-sensitivity functions of the visual system. *Journal of the Optical Society of America, 56,* 1141–1142.

Ross, J., & Speed, H. D. (1991). Contrast adaptation and contrast masking in human vision. *Proceedings of the Royal Society B: Biological Sciences, 246,* 61–69. [PubMed]

Schwartz, O., & Simoncelli, E. P. (2001). Natural signal statistics and sensory gain control. *Nature Neuroscience, 4,* 819–825. [PubMed] [Article]

Stromeyer, C. F., III, & Julesz, B. (1972). Spatial-frequency masking in vision: Critical bands and spread of masking. *Journal of the Optical Society of America, 62,* 1221–1232. [PubMed]

Viemeister, N. F. (1972). Intensity discrimination of pulsed sinusoids: The effects of filtered noise. *Journal of the Acoustical Society of America, 51,* 1265–1269. [PubMed]

Wichmann, F. A. (1999). *Some aspects of modelling human spatial vision: Contrast discrimination*. Unpublished doctoral dissertation, The University of Oxford, Oxford, UK.

Wichmann, F. A. (2004). Masking by plaid patterns revisited. In D. Kerzel, V. Franz, & K. R. Gegenfurtner (Eds.), *Experimentelle psychologie. Beiträge zur 46. Tagung experimentell arbeiten der Psychologen* (p. 285). Lengerich: Pabst Science Publishers.

Wichmann, F. A., & Henning, G. B. (2006). The pedestal effect is caused by off-frequency looking, not nonlinear transduction or contrast gain-control. In H. Hecht, S. Berti, G. Meinhardt, & M. Gamer (Eds.), *Experimentelle psychologie. Beiträge zur 48. Tagung experimentell arbeitender Psychologen* (p. 205). Lengerich: Pabst Science Publishers.

Wichmann, F. A., & Hill, N. J. (2001a). The psychometric function: I. Fitting, sampling, and goodness-of-fit. *Perception & Psychophysics, 63,* 1293–1313. [PubMed] [Article]

Wichmann, F. A., & Hill, N. J. (2001b). The psychometric function: II. Bootstrap-based confidence intervals and sampling. *Perception & Psychophysics, 63,* 1314–1329. [PubMed] [Article]

Wichmann, F. A., & Tollin, D. J. (1997a). Masking by plaid patterns is not explained by adaptation, simple contrast gain-control or distortion products. *Investigative Ophthalmology and Visual Science, 38,* S631.

Wichmann, F. A., & Tollin, D. J. (1997b). Masking by plaid patterns: Spatial frequency tuning and contrast dependency. *OSA Conference Program, 97*.

Yang, J., & Makous, W. (1995). Modeling pedestal experiments with amplitude instead of contrast. *Vision Research, 35,* 1979–1989. [PubMed]

Zwicker, E. (1956). Die Elementaren Grundlagen zur Bestimmung der Informationskapazität des Gehörs. *Acustica, 6,* 365–381.

Zwicker, E., (1970). Masking and psychological excitation as consequence of the ear's frequency analysis. In R. Plomp & G. Smoorenburg (Eds.), *Frequency analysis and periodicity detection in hearing* (pp. 376–394). Leiden: A. W. Sijthoff.