

The effect of notched noise on flicker detection and discrimination

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Flicker perception was investigated using two-alternative forced-choice detection and discrimination tasks with four different types of external noise: (1) broadband noise, (2) 5-Hz notched-noise—broadband noise with a 5-Hz band centered on the signal frequency removed, (3) 10-Hz notched-noise, and (4) no external noise. The signal was a burst of 10-Hz sinusoidal flicker presented in one of two observation intervals. In discrimination experiments, a pedestal—sinusoidal flicker with the same frequency, duration, and phase as the signal—was added to both observation intervals. With no noise, observers' performance first improved with increasing pedestal modulation, before deteriorating in accordance with Weber's Law, producing the typical "dipper" shaped plot of signal versus pedestal modulation. Noise affects performance, but the dipper effect persisted in each type of noise. The results exclude three models: the ideal-observer in which the pedestal improves performance by specifying the signal exactly; off-frequency-looking models in which the dipper depends on detection by channels tuned to temporal frequencies different from that of the signal; and strict energy detectors. Our data are consistent with signal processing by a single mechanism with an expansive non-linearity for near-threshold signal modulations (with an exponent of six) and a compressive "Weberian" non-linearity for high modulations.

Keywords: pedestal effect, noise, notched noise, flicker detection, flicker discrimination, off-frequency looking, uncertainty

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Introduction

Under certain conditions, the ability of a human observers to discriminate correctly which of two observation intervals contains a signal (sometimes called the target) can be improved by adding copies of the signal (usually called pedestals) to both intervals. This effect, known as the pedestal or dipper effect, runs counter to models in which the difference signal required for discrimination increases monotonically with background level as predicted by Weber's Law, in which the signal increases in proportion to the background level, or by the DeVries-Rose square-root law, in which it increases in proportion to the square-root of the background level.

The dipper effect is typically obtained in experiments in which the spatial and temporal properties of the signal and pedestal are matched in frequency, phase and orientation. The threshold-versus-contrast (TvC) function (in which the contrast [or modulation] of the signal corresponding to some percentage of correct responses is plotted against

the pedestal contrast) exhibits a characteristic "dipper" appearance—as pedestal contrast increases from zero, performance first improves, and then deteriorates at higher pedestal levels (see, for example, [Figure 1](#), below).

The earliest reports of the pedestal effect were for the discrimination of a flashed, uniform target superimposed on one of two spatially-separated flashed pedestals of the same size and duration (e.g., [Barlow, 1962a, 1962b](#); [Cornsweet & Pinsky, 1965](#); [Whittle & Swanston, 1974](#)), or for the discrimination of a grating presented on one of two temporally-separated gratings of the same spatial frequency and orientation ([Campbell & Kulikowski, 1966](#)).

The pedestal effect has received considerable attention in sensory research where it has been used as a means of investigating the suprathreshold properties of visual mechanisms. It has been used extensively in the spatial domain to investigate the response characteristics of channels or mechanisms that are differentially sensitive to spatial frequency and orientation (e.g., [Bird, Henning, & Wichmann, 2002](#); [Foley & Legge, 1981](#); [Henning & Wichmann, 2007](#); [Legge & Foley, 1981](#); [Nachmias &](#)

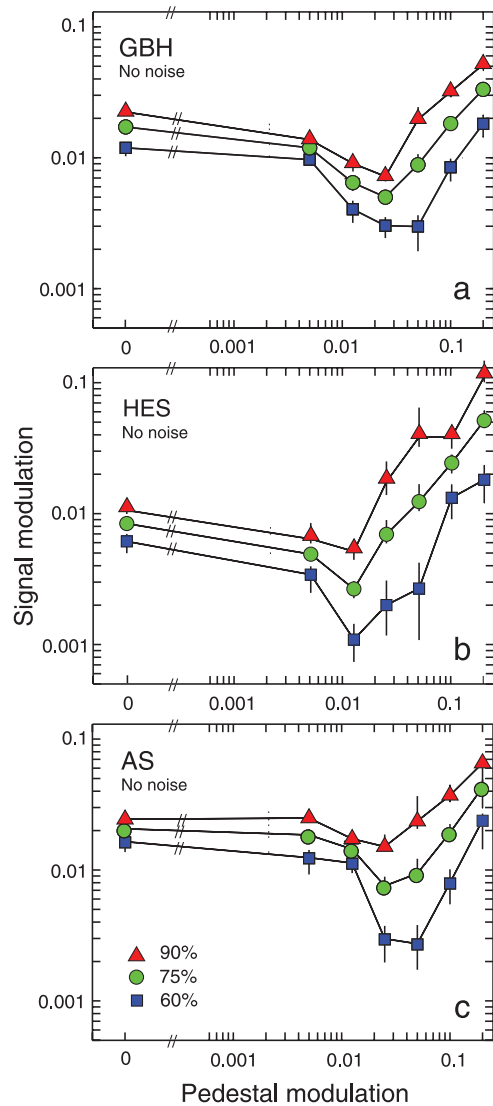


Figure 1. Data from the no-noise condition. Signal modulations corresponding to performance levels of 90% (red triangles), 75% (green circles), and 60% correct (blue squares) plotted as a function of the pedestal modulation. For each observer, the contours of constant performance were derived from Gumbell fits to the underlying psychometric functions at each pedestal level, based on at least five points, each of 100 observations (Wichmann & Hill, 2001a, 2001b). The logarithmic thresholds and their error estimates were converted to linear scales. The leftmost points were obtained with no pedestal. Vertical lines indicate ± 1 standard deviation derived from the maximum likelihood fits to the psychometric functions. Observers: GBH (a), HES (b) and AS (c).

Sansbury, 1974; Wichmann, 1999; Yang & Makous, 1995). But it has also been used to investigate the properties of, for example, color and luminance mechanisms (e.g., Chen, Foley, & Brainard, 2000; Cole, Stromeyer, & Kronauer, 1990; Mullen & Losada, 1994; Switkes, Bradley, & De Valois, 1988); and ON- and OFF-channels (e.g., Bowen, 1995). The effect has also been reported with flickering or drifting gratings (e.g., Anderson & Vingrys,

2001; Boynton & Foley, 1999; Stromeyer, Kronauer, & Madsen, 1984) and with uniform flickering targets (Anderson & Vingrys, 2000; Stockman & MacLeod, 1985).

Here, we use the pedestal effect in the temporal domain to investigate the response characteristics of mechanisms sensitive to temporal frequency.

So, by what mechanisms might increasing the pedestal contrast in both intervals improve performance? A number of more or less plausible explanations of the pedestal effect have been proposed (see Solomon, 2009 for recent review). Broadly speaking, they can be put into four categories:

- (1) The effect is the result of a specific nonlinear transducer function (e.g., Foley & Legge, 1981; Legge & Foley, 1981; Nachmias & Sansbury, 1974), such that the early part of the function is accelerating and the later part decelerating. The accelerating portion generates the dipper, because the difference in output between signal-plus-pedestal and the pedestal alone is larger than the difference in output between the signal alone and no signal, while the decelerating portion produces Weber's Law by compression. In some versions, the deceleration is produced by a divisive gain control (e.g., Boynton & Foley, 1999; Foley, 1994).
- (2) The effect is due to a specific nonlinear transducer function combined with a signal-dependent internal noise (e.g., Green, 1967; Kontsevich, Chen, & Tyler, 2002), such that the accelerating nonlinearity produces the dipper at low pedestal levels, while the noise produces Weber's Law at high levels.

In both categories (1) and (2), the pedestal effect is assumed to be a characteristic of a single mechanism.

- (3) Perhaps the most radical proposal is that the effect, in spatial vision at least, is due not to the characteristics of a single mechanism but to the pooled characteristics of many mechanisms with non-linear transducer functions that are insufficient in themselves to produce substantial dippers. The dipper is assumed to be produced by the recruitment of mechanisms that are mistuned away from the signal and pedestal as the pedestal contrast first increases (Goris, Wichmann, & Henning, 2009; Henning & Wichmann, 2007). We refer to these models as the "off-frequency-looking" model.
- (4) Another, now somewhat discredited proposal (e.g., Bowen, 1995; Yang & Makous, 1995), is that the pedestal, because it is a copy of the test, reduces uncertainty about the frequency, phase, timing, and location of the signal thereby producing improved performance and the dipper (Pelli, 1985).

Here we use a similar strategy to Henning and Wichmann (2007) to evaluate these models, but applied in the temporal rather than spatial domain. We measured

138 thresholds for detecting Hanning-windowed bursts of
 139 10-Hz sinusoidal flicker in one of two temporal intervals
 140 containing pedestals of the same temporal frequency, phase
 141 and duration as a function of pedestal contrast (i.e., TvC
 142 functions). Measurements were made under four conditions
 143 of external noise: 1) broadband noise, 2) 5-Hz “notched”
 144 noise—the same broadband noise from which a 5-Hz band
 145 of noise centered arithmetically on the signal frequency
 146 had been removed, 3) 10-Hz notched noise and 4) no
 147 external noise. Comparisons among the no-noise and noise
 148 conditions, allow us to evaluate the different models
 149 proposed to account for the dipper effect. If off-frequency
 150 looking is important in producing the dipper, then the
 151 use of notched-noise should minimize the contributions
 152 of off-frequency channels and thus destroy the dipper
 153 (as Henning and Wichmann (2007) found in the spatial
 154 domain). If, on the other hand, uncertainty reduction is
 155 important, then, for an ideal observer (for whom the
 156 pedestal defines the signal frequency precisely), changing
 157 the notch width of the noise should not affect the
 158 observer’s performance when the pedestal is present.

159 Because the dipper persists in notched temporal noise,
 160 and because performance depends on the notch width, our
 161 results are inconsistent with off-frequency looking in the
 162 temporal domain and with uncertainty reduction as
 163 characterized by the signal-known-exactly (SKE) ideal-
 164 observer. Instead, our data can be accounted for by
 165 assuming a single channel with an appropriate nonlinear
 166 transducer function. Following the early proposals of
 167 Delboeuf (1873) and Fechner (1860), we develop a simple
 168 nonlinear transducer function that describes our entire
 169 data set. The development of this model is described in
 170 the final section of the paper. This modeling suggests that
 171 the dipper effect cannot be characterized by a simple energy
 172 detector. Instead, the required transducer has a steeply-
 173 rising threshold non-linearity with an exponent of about
 174 six (i.e. three times that of a simple energy detector).
 175

176 Methods

178 Subjects

179 Two males (aged 50 and 64) and one female (aged 30)
 180 participated in this study. The study conforms to the
 181 standards set by the Declaration of Helsinki, and the
 182 procedures were approved by local ethics committees at
 183 University College London.
 184

185 Procedure

186 We used a two-interval forced-choice task. On each
 187 trial, noise and pedestals (if used) were both presented in
 188 two 1-second long observation intervals separated by a
 189 500-millisecond pause. The signal was added to one of the

190 observation intervals of each trial. The interval that
 191 contained the signal was randomly selected, so that the
 192 signal was equally likely to be in the first or second
 193 interval. Following the second observation interval, there
 194 was a 1.5 second response interval during which the
 195 observers indicated, by pressing keys, which interval they
 196 thought had contained the signal. Auditory signals indi-
 197 cated the beginning of each observation interval and the
 198 start of the response interval. Feedback was provided by a
 199 fourth auditory signal that indicated which observation
 200 interval had contained the signal. Psychometric functions
 201 of at least five points of 100 observations each were
 202 obtained in blocked sessions relating the percentage of
 203 correct responses to the amplitude of the signal for each
 204 pedestal level and notch width. These measurements were
 205 obtained in four conditions of external noise: 1) no noise;
 206 2) broadband noise, 3) 5-Hz “notched” noise, 4) 10-Hz
 207 notched noise. The order of sessions was counterbalanced
 208 within observers.
 209

210 Apparatus

211 Flickering stimuli were presented on an LED-based
 212 photo-stimulator that allows fine control of the luminance
 213 of bright uniform fields up to high temporal frequencies
 214 (Pokorny, Smithson, & Quinlan, 2004; Puts, Pokorny,
 215 Quinlan, & Glennie, 2005). The output of the LEDs was
 216 controlled via an M-Audio soundcard, housed in a G3
 217 Macintosh computer. A circular test field, comprised of
 218 light from four LEDs (with peak outputs at 460, 516, 558,
 219 and 660 nm), had an annular surround, comprised of light
 220 from a second set of four LEDs with peak outputs at the
 221 same wavelengths. The test field subtended 2 degrees of
 222 visual angle and the annular surround subtended 8 degrees.
 223 To minimize the contrast at the border between the central
 224 and surround fields, each of the surround LEDs in turn was
 225 perceptually matched to the center LED having the same
 226 wavelength composition. The relative levels of the four
 227 central LEDs were chosen such that the fields were
 228 metamers of the equal-energy spectrum, and appeared
 229 approximately achromatic. In this study, the luminances
 230 of the surround LEDs were held constant, and the four
 231 LEDs illuminating the central test field were modulated
 232 in-phase to produce variations in luminance. The mean
 233 luminance of both the surround and the central field was
 234 30 cd/m^2 , which was sufficient to guarantee rod saturation.
 235

236 Specification of stimuli

237 The LED spectra were measured with a telescopic
 238 spectroradiometer (Gamma Scientific, San Diego, CA)
 239 and used in conjunction with estimated cone sensitivities
 240 (Stockman & Sharpe, 2000) to calculate the ratio of the
 241 outputs of the component LEDs required to produce a
 242 light metameric to equal energy white. The relation

between the intensities specified by the program and those produced by the diodes was established with a radiometer (UDT Instruments, Orlando, FL). A linearizing look-up table was then created to generate a mapping from the level requested in software to the luminance output of each LED. The system calibrated in this way should allow accurate luminance modulations with a resolution of 16.5 bits per channel up to about 100 Hz (Puts et al., 2005). The temporal waveforms were generated digitally and loaded to a buffer (wavetable) using the CoreAudio commands in Mac OS X.

Each stimulus had a duration of 1 second, which corresponded to 44100 samples at the sampling rate of the soundcard. All temporal waveforms were first generated in software using MATLAB. The 10-Hz signals and pedestals were generated as simple sinusoidal waveforms. The noise waveforms were defined as linear combinations of sinusoids from a set whose frequencies were equally spaced at 1 Hz intervals up to 100 Hz. At each frequency, the amplitudes of both sine- and cosine-phase sinusoids were randomly selected from a Gaussian distribution of zero mean and fixed variance. Broadband noise of this sort is sometimes called Fourier-series band-limited white Gaussian noise. The variance of the Gaussian distribution is proportional to the mean noise-power density of the noise and we describe below how we chose the appropriate variance. Notched noise was produced by removing either a 10- or 5-Hz band of components from a region centered arithmetically on the 10-Hz signal and pedestal frequency. The signals, in the frequency domain, were then transformed to the time domain.

We generated 100 noises in each noise class (meeting the criteria set out below). The noises were stored and, for each observation interval of our two-alternative forced-choice task, we randomly chose a noise from the appropriate class, each member of which was equally likely to be chosen. The waveform that was displayed was constructed by summing the appropriate signal, pedestal, and noise waveforms, multiplying the resultant waveform by a raised cosine (Hanning) window, rounding, and integerizing the windowed stimulus. The signal and pedestal were always in phase and in cosine phase with the peak of the window.

Calibration

To check the characteristics of the stimuli, a nominally sinusoidally flickering luminance was produced by the diodes and examined with the photometer. The photometer produced an electrical signal that followed the luminance input without loss up to about 100 Hz. We examined the harmonic content of a 10-Hz (nominally) sinusoidal flicker by sending the electrical output of the photometer through a wave analyzer (HP 35080A). This established that the stimulus was effectively sinusoidal since its second and third harmonic distortion products were negligible.

The photometer and the wave analyzer were also used to establish the characteristics of the flickering Gaussian noise. One-second long examples of the broadband noise and the 10-Hz notched noises were generated in MATLAB, rounded, integerized, displayed as repeating luminance waveforms through the diodes, and observed at the wave analyzer as the electrical signals from the photometer.

We chose the appropriate variance for the generation of the Gaussian noise by considering two related criteria: First we inspected the output from the diodes in response to broadband noise and increased the variance until the waveform was only very occasionally limited (clipped) by the maximum or minimum output; second, with the chosen value of the variance, we looked at the frequency spectrum of the notched noise using the wave analyzer. Notch depth is adversely affected either by excessive clipping (produced by too large a variance) or by insufficient dynamic range in the numerical representation prior to digital-to-analogue conversion (produced by too small a variance). For each noise sample we used, we confirmed that our 10-Hz notch had a stop-band in which the noise-power density was at least 35 dB below the noise-power density in the pass-band. A similar analysis of the 5-Hz notches was precluded by the finite bandwidth (1-Hz at half-power) of the narrowest filter in the wave analyzer. The mean root-mean-squared (r.m.s.) contrast of the 100 broadband noise samples used was 0.198, with a standard deviation of 0.008.

Results

Data obtained in the absence of external noise

The psychometric functions relating the percentage of correct responses to the logarithm of the depth of signal modulation were fit with Gumbel functions using the maximum-likelihood procedure of Wichmann and Hill (2001a, 2001b). Estimates of the modulation depths corresponding to 60%, 75%, and 90% correct responses, together with estimates of the variability associated with each estimate, were determined from these fits.

Figure 1 presents conventional threshold vs. pedestal functions, called threshold vs. contrast plots or TvC plots. Each panel shows, for a different observer, the signal modulation (or ripple ratio) corresponding to three different performance levels—90% correct (red triangles), 75% correct (green circles), and 60% correct (blue squares)—each as a function of the pedestal modulation; no external masking noise was used. Where larger than the data points, vertical lines indicate approximately ± 1 standard deviation. The results are broadly similar for the three observers, and the pattern of results is roughly similar across the different performance levels: the contours of

352 constant performance—which we refer to loosely as
 353 “thresholds”—first fall as the pedestal modulation
 354 increases from zero, and reach minima well below the
 355 “threshold” modulation depth obtained with no pedestal,
 356 before rising again. The minima are located at pedestal
 357 modulations just above the “threshold” modulations
 358 obtained with no pedestal. Comparable “dipper” shapes
 359 have been found in many other analogous experiments.

360 In spatial vision, the depth of the dipper and the location
 361 of its minimum depend on performance level: the dipper
 362 exhibited for low performance levels is deeper and occurs
 363 at higher pedestal levels than the dipper exhibited for
 364 higher performance levels (Bird et al., 2002; Goris,
 365 Wagemans, & Wichman, 2008; Wichmann, 1999). Simi-
 366 larly, for flicker, we find that the maximum improvement
 367 with added pedestal modulation is greater at lower than at
 368 higher performance levels and tends to occur at slightly
 369 higher pedestal modulations. The change in shape with
 370 performance level reflects the slopes of the underlying
 371 psychometric functions relating percentage correct to the
 372 logarithm of signal modulation, which are steepest at low
 373 pedestal levels, where the performance level contours are
 374 closely spaced, and most shallow in the vicinity of the dip,
 375 where the performance contours are most widely separated.
 376 The performance contours become more closely spaced
 377 once again on the rising portions of the curves where the
 378 pedestals mask the discrimination of the signal roughly in
 379 accordance with Weber’s Law.

380

381 Data obtained with external noise added

382 We next consider the same detection and discrimination
 383 experiment performed in the presence of the three types of
 384 noise: 1) broadband, white Gaussian noise, 2) 5-Hz
 385 notched noise—the same broadband noise from which a
 386 5-Hz band of noise arithmetically centered on the signal
 387 frequency had been removed, and 3) 10-Hz notched noise.

388 The three panels of Figure 2 show, separately for each
 389 observer, the 75% performance contours in the same
 390 format as Figure 1—the signal modulation producing 75%
 391 correct as a function of pedestal modulation. The black
 392 symbols are from the broadband-noise condition, the dark
 393 gray symbols from the 5-Hz-notch condition, the light gray
 394 symbols from the 10-Hz-notch condition, and the open
 395 symbols, from Figure 1, are from the no-noise condition.
 396 Error bars indicate approximately ± 1 standard deviation.
 397 For all three observers the results vary systematically with
 398 the noise masking condition. Two changes are apparent
 399 with increasing notch width. First, the performance for the
 400 detection of the signal alone (i.e., the leftmost points in
 401 Figure 2) improves. Second, the region of masking by the
 402 suprathreshold pedestals begins at lower pedestal levels—
 403 and the pedestal value at which the best performance
 404 occurs decreases slightly—as notch width increases.

405 In Figure 3, we present the 60%, 75% and 90%
 406 performance contours for all conditions of the experiment

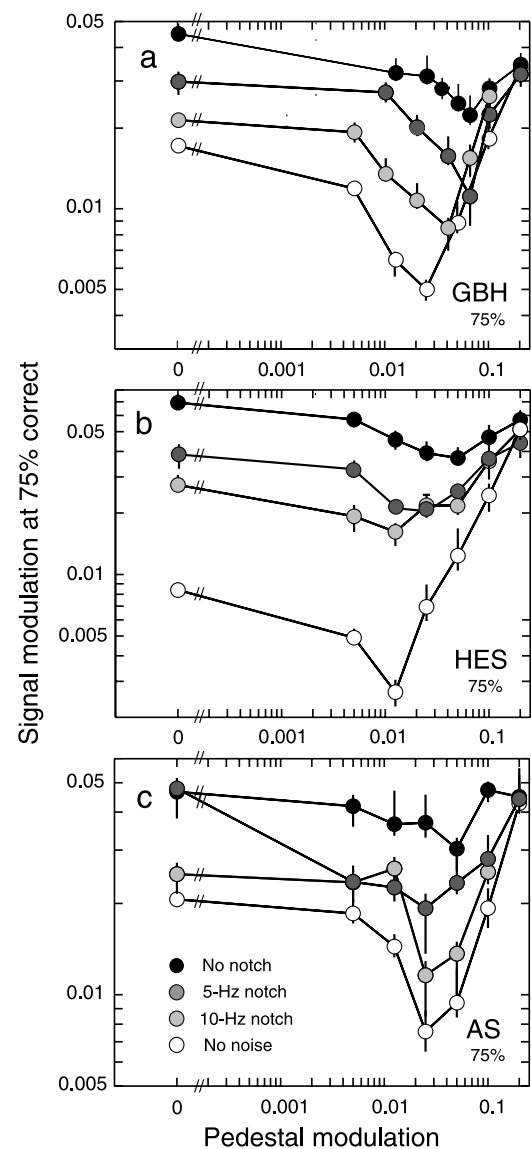


Figure 2. Signal modulations corresponding to 75% correct performance plotted as a function of pedestal modulation. Four different masking conditions are shown: data obtained with broadband white Gaussian noise (black circles), broadband noise from which a 5-Hz notch arithmetically centered on the signal frequency was removed (dark gray circles), broadband noise with a 10-Hz notch centered on the signal frequency (light gray circles), and with no noise (open circles, from Figure 1). Error bars were derived in a same way as for Figure 1. Observers: GBH (a), HES (b) and AS (c).

The three columns of plots show data for GBH (left), HES (middle) and AS (right). Plots in the top row show the results obtained with no external noise, and subsequent rows show data obtained with notched-noise maskers with a 10-Hz notch, notched-noise maskers with a 5-Hz notch and broadband noise maskers. Each plot compares data for the three performance levels: 60% contours (blue squares), 75% contours (green circles), and 90% contours (red

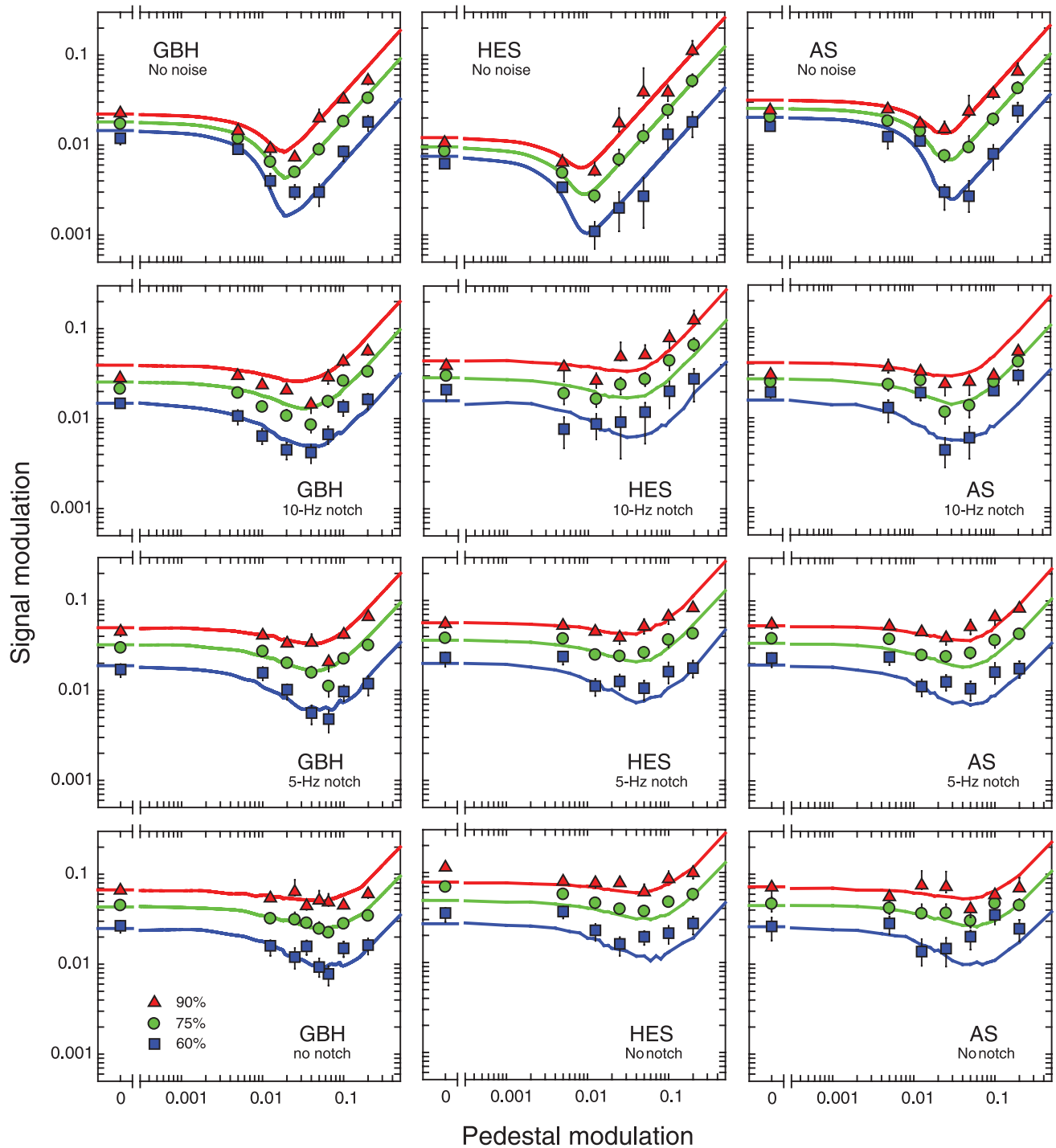


Figure 3. Data from four different masking conditions: no-noise (top row), broadband noise with a 10-Hz notch centered on the signal frequency (second row), broadband noise with a 5-Hz notch centered on the signal frequency (third row), and broadband white Gaussian noise (bottom row), for three observers: GBH, HES, AS. In each panel, signal modulations corresponding to performance levels of 90% (red triangles), 75% (green circles), and 60% correct (blue squares) are plotted as a function of the pedestal modulation. Smooth lines through the data are the best fitting curves from the non-linear transducer model of Equation 12. Details of simulation and fitting are provided in the text.

415 triangles). The solid lines through the data points show the
 416 best-fitting predictions of a model simulation described in
 417 the section “Development of a non-linear transducer
 418 model”.

There is considerable variability among the observers, 419
 but many of the differences are due simply to differences 420
 in the observers’ sensitivities. There are also several 421
 features of the data that are common to all three observers. 422

423 Associated with the improvement in performance level
 424 with increasing notch width for the detection of the signal
 425 alone (leftmost points), there is an accompanying increase
 426 in the separation between the performance contours
 427 defined by the data. Thus, increasing notch width causes
 428 the underlying psychometric functions to become steeper.
 429 One failure of our model predictions (shown by the
 430 continuous lines in Figure 3, and described later) is that
 431 the predicted contours at the detection threshold are
 432 approximately equally separated across the three noise
 433 conditions. As we discuss below, the changes we observe
 434 are also inconsistent with the uncertainty model. As in
 435 Figure 2 for the 75% contour, the contours at 60% and
 436 90% also show that the extent of masking decreases with
 437 notch width, but that the facilitation—the dipper—persists
 438 across all conditions.

439 The characteristics of the contours at different perfor-
 440 mance levels apparent in the absence of external noise
 441 shown in Figure 1 are preserved in the presence of
 442 external noise: The size of the dipper depends on
 443 performance level, with the smallest improvement for
 444 the 90% performance contour and greatest improvement
 445 for the 60% contour. For GBH the dipper occurs close to,
 446 or slightly above, the detection threshold for the signal
 447 alone. This pattern is repeated for HES and AS, although
 448 the data are sometimes too noisy to locate the minima
 449 precisely. In general, in external noise conditions, the
 450 location of the dipper shifts to higher pedestal modu-
 451 lations compared to the location of the dipper in the
 452 absence of external noise.

453
454

455 **“Threshold” signal modulation**
 456 **as a function of the combined**
 457 **strength of signal and pedestal**
 458

459 Some insight into the results can be obtained by plotting
 460 the signal modulation corresponding to some performance
 461 level against the combination of that signal modulation
 462 and the pedestal modulation (the modulations simply add in
 463 the combination because they are of the same frequency
 464 and phase). From the point of view of an observer, the task
 465 is either a detection or discrimination task, depending on the
 466 strength of the pedestal modulation. At low pedestal levels
 467 the task seems to the observer to be a detection task
 468 because the pedestal alone is never seen, whereas at high
 469 pedestal levels it seems to be a discrimination task—with
 470 the pedestal modulation alone in one interval and the
 471 signal-plus-pedestal modulation in the other.

472 Figure 4 shows the data for GBH from Figure 1 (no-
 473 noise condition) re-plotted with signal modulation as a
 474 function of signal-plus-pedestal modulation. In the top
 475 panel the signal modulation corresponds to 60% correct
 476 responses, in the center panel, to 75% correct, and in the

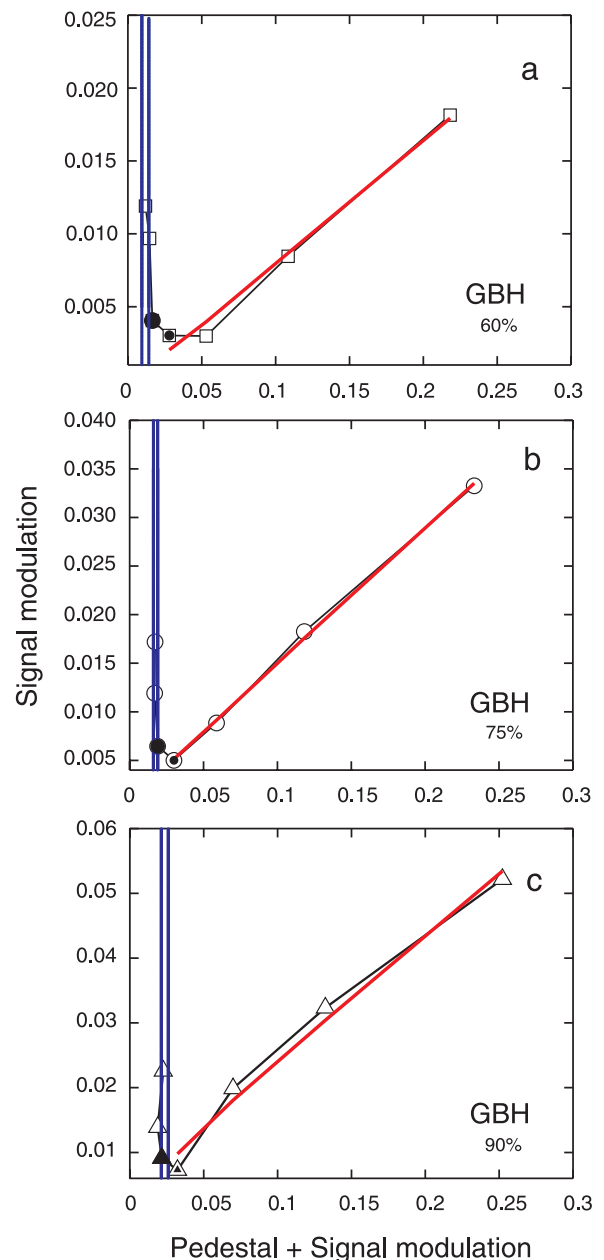


Figure 4. Data obtained in the no-noise condition (from Figure 1) for observer GBH plotted against different co-ordinates: each panel shows signal modulation as a function of signal-plus-pedestal modulation for 60% (a), 75% (b) and 90% (c) correct responses. The extended blue vertical lines in each panel mark the 95% confidence interval about the signal modulation required to achieve the appropriate performance level with zero pedestal modulation. The filled symbol in each panel marks the data point where the pedestal modulation alone is close to the 60% “threshold” and the partially filled symbol marks the data point where the pedestal alone is close to the 90% threshold. The red diagonal lines show the best (least squares) linear fit to the rightmost four points in each panel.

bottom panel, to 90% correct. The extended vertical lines (in blue) toward the left in each panel mark the 95% confidence interval around the signal modulation required to achieve that performance level in detecting the signal alone (i.e., with zero pedestal modulation). The approximate confidence intervals were obtained from the bootstrap procedure of Wichmann and Hill (2001a, 2001b). The red diagonal lines are the best (least squares) fits to the rightmost four points in each panel.

These graphs have several notable features. First, at low pedestal levels, the signal is discriminated when the signal-plus-pedestal modulation reaches the level at which modulation can be detected in the absence of the pedestal. For these pedestals of low modulation depth, the task is essentially a detection task; the pedestal alone is very rarely seen and the only interval with recognizable sinusoidal modulation comprises the pedestal modulation added to the signal modulation. The pedestal effect is produced because, in this region (i.e., for pedestal levels approaching the bottom of the dipper in Figure 1), it is the sum of the pedestal and signal modulation that produces the “threshold” stimulus; the signal modulation needed to reach the “threshold” decreases as the pedestal modulation increases and thus appears as the pedestal or dipper effect. This seems to be the case for all three performance thresholds.

Second, a narrow transition region begins at the point at which the modulation of the pedestal alone begins to be “seen”. This transition region is delimited in each panel by the large and small filled symbols, which mark the approximate points on each curve at which the modulation of the pedestal reaches levels at which the pedestal alone should be detected with performance levels of 60% and 90%, respectively. In the transition region, the performance results from a mixture of detection-like trials, in which flicker with the temporal and spatial characteristics of the signal is seen in only one observation interval, and discrimination-like trials in which that flicker is seen in both intervals and the interval containing the more pronounced flicker (or flicker more like that of the signal) is chosen as having contained the signal. This region in Figure 4 is very small and corresponds, in effect, to the width of the psychometric function relating the percentage of correct responses to the depth of signal modulation in the absence of a pedestal.

Lastly, at higher pedestal levels, the signal modulation corresponding to a given performance level is proportional to the sum of signal and pedestal modulations. The red diagonal lines fitted to the upper three or four discrimination thresholds show the best (least squares) linear fit to the data in that region. The fitted function is of the form:

$$\Delta M = m(\Delta M + M) + c, \quad (1)$$

where m is the slope and c the intercept. All three observers produce results of the form of Figure 4 in the

Observer	Weber		“Intercept”	t
	%	Fraction		
GBH	60	0.091	-.00155	t1.1
	75	0.139	.00101	t1.2
	90	0.176	.00696	t1.3
HES	60	0.089	.00007	t1.4
	75	0.208	-.00077	t1.5
	90	0.348	-.00089	t1.6
AS	60	0.127	-.00414	t1.7
	75	0.183	-.00161	t1.8
	90	0.218	.00604	t1.9
Average	60	0.102	-.00187	t1.10
	75	0.177	-.00046	t1.11
	90	0.247	.00403	t1.12

Table 1. Weber fractions obtained at high pedestal levels corresponding to the percentage correct obtained in the no-noise condition and the corresponding intercepts of the least-squares linear fit to the rising sections of plots like those in Figure 4 for each observer and the average observer.

condition with no external noise. In all cases, the intercepts, c , are close to zero. The largest 95% confidence interval for the intercept, -0.030 to 0.029 , was for the 90% performance contour for observer HES; all the remaining confidence intervals were within 0.01 of zero. This result is important, because it implies that in the regions in which performance can be described by Equation 1 it is governed, as in many discrimination tasks, by something like Weber’s law; and it also means that the Weber fraction, $\Delta M/M$, can be extracted from the slopes of the linear fits. Rearranging Equation 1 with $c = 0$ gives:

$$\Delta M/M = m/(1 - m). \quad (2)$$

This is, of course, not a general finding, since not all contrast discrimination conforms to Weber’s Law.

In Table 1, we summarize the fits of Equation 1 by tabulating the Weber fractions calculated using Equation 2 and the intercepts. The Weber fractions for modulation discrimination when the signal and pedestal have the same frequency and are in-phase correspond to the ratio of the signal modulation (at some “threshold” performance level) to the pedestal modulation. The average Weber fractions across the three observers are: 0.102, 0.177, and 0.247 for the 60%, 75%, and 90% performance contours, respectively.

For the conditions with noise, plots of the form of Figure 4 show similar characteristics to those obtained without noise. For example, data obtained for HES in the broadband noise condition are shown in Figure 5. In general, the interpretation of these plots for the conditions with external noise is slightly more difficult for two reasons: First the external noise introduces more variability (evident in the increased widths of the vertical blue lines giving the 95% confidence intervals for the

633 generation of the dipper, in which case they would pose a
634 problem for off-frequency looking models, *in general*.
635 However, off-frequency looking across spatial-frequency
636 channels cannot be excluded by the results of our
637 experiment.

638 The off-frequency looking model in spatial vision can
639 be preserved by supposing that there is something
640 fundamentally different between channels sensitive to
641 temporal frequency and those sensitive to spatial fre-
642 quency. One well-known difference is that there are fewer
643 temporal frequency channels than spatial ones. Most
644 estimates suggest two, or possibly three, flicker mecha-
645 nisms (Boynton & Foley, 1999; Hess & Snowden, 1992;
646 Levinson, 1960; Mandler & Makous, 1984; Roufs, 1974;
647 Watson, 1986). By contrast, there are likely to be many
648 spatial frequency channels (Blakemore & Campbell,
649 1969; Campbell & Robson, 1968; De Valois & De Valois,
650 1988; Graham & Nachmias, 1971; Henning, 1988;
651 Henning, Hertz, & Hinton, 1981). Differences in channel
652 numerosity alone, however, cannot explain why individual
653 temporal frequency channels can sustain the full dipper
654 effect, but individual spatial-frequency channels cannot.
655 One possibility is that the temporal frequency channels
656 have different underlying transducer functions, perhaps
657 with a harder threshold nonlinearity, and perhaps medi-
658 ated or limited by mechanisms earlier in the visual system
659 than the emergence of spatial frequency channels.

660 It is also possible that the flicker response to our
661 spatially-uniform flickering disc is mediated by a family
662 of spatio-temporal channels optimally tuned to different
663 (low) spatial frequencies. If the transducer functions of
664 these spatial-frequency sensitive channels are similar to
665 those tuned to the higher spatial frequencies investigated
666 by Henning and Wichmann (2007), then the dipper that
667 we find might also result from pooling across the spatial
668 frequency domain.

670 Uncertainty reduction models

671 TvC functions measured under different conditions of
672 external noise have also allowed us to evaluate explana-
673 tions of the dipper effect based on uncertainty reduction.
674 Such explanations suppose that the improvement in
675 performance in the presence of the pedestal results from
676 the pedestal improving the observer's knowledge of the
677 characteristics of the signal (Burgess, 1985, 1990; Green
678 & Swets, 1966; Pelli, 1985).

679 Uncertainty reduction models of the pedestal effect are
680 typically assessed by comparing human performance with
681 that of the ideal observer for a signal-known-exactly
682 (SKE) (Burgess, 1985, 1990; Pelli, 1985). An ideal detec-
683 tion process takes advantage of full knowledge of the
684 signal's waveform to filter out irrelevant frequencies and
685 phases. Our unfiltered noise stimuli consist of sine and
686 cosine components at 100 frequencies, each having iden-
687 tical independent Gaussian distributions of amplitude over

688 trials so that the stimulus on a given trial defines a point in
689 a 200 dimensional space. For a known signal, only one of
690 the 200 dimensions is relevant, and the noise components
691 for the other 199 dimensions can be ignored. But we show
692 that this does not happen.

693 The ideal observer can be realized by using as the
694 decision axis the output of a device that calculates the
695 cross-correlation of the input (noise alone or signal plus
696 noise) with a copy of the known signal (Green & Swets,
697 1966; van Trees, 1968). For sinusoidal signals, a cross-
698 correlation mechanism is sensitive to only one component
699 of the noise—that component having the same frequency
700 and phase as the signal. Changing the width of a notch
701 centered on the signal frequency has no effect on a cross-
702 correlation receiver's performance and thus, if the cross-
703 correlator is an adequate model of human behavior,
704 changing notch widths should not affect human perfor-
705 mance which, for both our notch widths, should be the
706 same as having no external noise at all.

707 Our data, however, consistently show that performance
708 varies systematically with the noise-masking condition.
709 As described in the Results section, with increasing notch
710 width the performance for the detection of the signal alone
711 improves, and the underlying psychometric functions
712 become steeper. These results are inconsistent with the
713 behavior of the SKE ideal observer and indicate that the
714 mechanism detecting the flicker responds to flickering
715 noise of broad bandwidth rather than to a narrow band or
716 to a single noise component like the ideal observer for the
717 signal-known-exactly.

718 At the other extreme, if nothing is known about the
719 frequency and phase of the signal, no such pruning of
720 the stimulus space is possible; a stimulus located far from
721 the origin in any direction is more likely to have
722 originated from a signal plus noise rather than from noise
723 alone, so the appropriate decision axis for an unknown
724 signal is distance from the origin—the square root of the
725 sum of squares of the sine and cosine amplitudes at all
726 frequencies, which is monotonically related to the total
727 flicker energy of the stimulus. We consider the energy
728 detector subsequently.

729 Between the extremes of the SKE ideal observer and the
730 energy detector there are many possible forms of
731 uncertainty reduction—the coarse temporal-frequency
732 discrimination of Mandler and Makous (1984), or the
733 partition into 'agitation' as opposed to the luminance
734 'swell' visible at lower modulation frequencies (Roufs &
735 Blommaert, 1981) suggest several—but their exploration
736 is beyond the scope of this paper.

738 Non-linear transducer models

739 We argue that our results are broadly consistent with
740 the behavior of a single mechanisms characterized either
741 by a specific nonlinear transducer function (e.g., Foley &
742 Legge, 1981; Legge & Foley, 1981; Nachmias & Sansbury,

each observation interval of a trial, a logarithmically compressed neural signal deviates from its expected value $R(M) = \log_e(M/M')$ by the addition of Gaussian noise having a standard deviation, σ , independent of R (i.e., we assume the internal noise after the transducer is constant), then equal differences in R (and correspondingly equal fractional increases in M) will be detected with equal reliability whatever the starting value of R .

This provides a statistical and mechanistic “neo-Fechnerian” basis for Weber’s Law. By this account, the Weber fraction w is set by the noise standard deviation σ , which has the same units as R and can be thought of as the equivalent root-mean-squared (r.m.s.) variation in the stimulus modulation from observation-interval to observation-interval, expressed as a fraction of the mean modulation M . The difference in R between two intervals with modulations M and $(1 + w)M$ is distributed with standard deviation $\sqrt{2}\sigma$ around its mean of $\log_e(1 + w)$, which is approximately w when w is small. Referring this to the cumulative Gaussian distribution, σ is equal to the Weber fraction w for a criterion of 76% correct 2AFC performance.

Generalizing Fechner: Hard threshold model

$R(M)$ as defined above decreases smoothly toward zero as the modulation M decreases to M' . But when M is less than M' , R becomes negative, and it becomes increasingly negative without limit as M approaches zero (as indicated by the black curve of Figure 6). Fechner (1860) dealt with this unwelcome feature of the log transform by suggesting that the negative values of R correspond to ‘unconscious sensations’ that are all introspectively equivalent to one another, since none are consciously registered. As Fechner’s contemporaries were quick to point out (e.g., Müller, 1878), a simple and natural alternative proposal is that the sensory response R simply remains zero for all $M < M'$. With this assumption, Fechner’s log transform is truncated, replacing the negative values by zero (i.e., the lower-most blue line in Figure 6). The threshold modulation for eliciting a nonzero response, M' , divides the response-modulation function into two regions. Below M' the response is zero, above M' it is positive and logarithmically compressed (though, approximately linear just above threshold where M is not much greater than M'):

$$R = \begin{cases} 0 & \text{for } M \leq M' \\ \log_e(M/M') & \text{for } M > M', \end{cases} \quad (6)$$

or equivalently,

$$R = \max[0, \log_e(M/M')] \quad (7)$$

Just as the log transform provides a Fechnerian basis for Weber’s Law, the threshold nonlinearity at M' in Equation 7

provides a Fechnerian basis for the dipper. All subthreshold modulations $M \leq M'$ yield the same (zero) response, so pedestal and signal modulations that by themselves produce zero response can combine to produce a modulation that is discriminable from the (zero) response generated by the pedestal alone.

With the assumption introduced above, that the response R is contaminated by additive Gaussian internal noise of fixed variance, Equation 7 predicts performance in our experiments fairly well. Figure 7 shows the data for observer HES (replotted from the center panel of Figure 1) and the solid lines show the performance contours predicted by the model, and fitted with M' and σ as free parameters, estimated iteratively by using MATLAB’s *fminsearch* function (based on the Nelder-Mead algorithm) to minimize the mean squared error of prediction in $\log_e(M)$. On each iteration, Equation 7 was used to evaluate the mean response, R_p for each experimental pedestal modulation, M_p (assuming the trial value for M'); the mean signal-plus-pedestal response required for criterion discrimination performance was then obtained as $R_{crit} = R_p + \sqrt{2}\sigma z_{crit}$, where z_{crit} is the standard normal deviate corresponding to the criterion percent correct, respectively 0.253, 0.674 and 1.282 for 60%, 75% and 90% correct responses. Equation 7 was inverted to determine the total modulation of signal and pedestal M_{crit} needed for the response R_{crit} , and then the required signal modulation M_s was obtained as $M_s = M_{crit} - M_p$.

Comparable fits were obtained for the other two observers, AS and GBH. The dippers predicted by this hard-threshold model tend to be a little deeper than ones observed, and the predicted psychometric functions with weak pedestals are slightly steeper than observed, as reflected in the tight spacing of the contours for different performance levels. But the transition from steep psychometric functions with weak pedestals to shallower ones with large pedestals is well

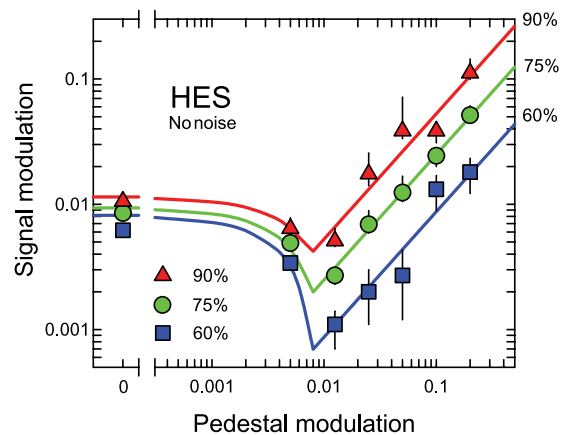


Figure 7. Data obtained in the no-noise condition (from Figure 1) for observer HES. Solid lines through the data are the best fitting curves from the hard-threshold model of Equation 7. Details of fitting are provided in the text.

881 predicted. The free parameters for the predictions of [Figure 7](#)
882 are $M' = 0.0075$, and $\sigma = 0.118$.
883

884 **Generalizing Fechner: Small-signal linearity**

885 In Fechner's time the dipper was neither experimentally
886 recognized nor theoretically anticipated, but it was clear
887 that Weber's Law had to be modified to accommodate
888 small background stimulus magnitudes, since the simple
889 formulation $\Delta M = wM$ implies discriminative capacity that
890 improves without limit as background magnitude is
891 decreased, contrary to observation. For many discrim-
892 ination tasks, where no dipper is observed, a modified
893 form of Weber's Law applies: the detectable stimulus
894 increment has a progressive, linear relation to the
895 combination of background stimulus magnitude M and a
896 constant M' to which it is added:

$$897 \Delta M = w(M + M'). \quad (8)$$

898 In this formulation, M' is no longer the stimulus associated
899 with zero response. In early discussions of intensity
900 discrimination (Delboeuf, 1873), M' was regarded as the
901 equivalent intensity of an effective background stimulus
902 or 'intrinsic light,' always present and added to any
903 external stimulus.

904 Delboeuf (1873) proposed an amendment to Fechner's
905 logarithmic formula to make it consistent with this 'linear
906 generalization' (Luce, 1959) of Weber's Law. This he did
907 by simply substituting $(M + M')$ for M in Fechner's
908 logarithmic formula, yielding:

$$909 R(M) = \log_e[(M + M')/M'] \quad (9)$$

$$910 = \log_e[1 + M/M'].$$

911 The red curves in both panels of [Figure 6](#) depict this
912 relation. As can be seen, zero response to zero stimulus is
913 still implied, but there is no sub-threshold dead zone.

914 **Further generalization to incorporate intermediate** 915 **(soft threshold) cases**

916 The hard threshold of [Equation 7](#) and the small-signal-
917 linearity of [Equation 9](#) can both be subsumed within a
918 'soft threshold' class of models that allow the gradient
919 dR/dM to increase with various degrees of smoothness in
920 the near-threshold range:

$$921 R = \log_e\{[1 + (M/M')^n]^{1/n}\} \quad (10)$$

$$922 = \log_e[1 + (M/M')^n]/n.$$

923 Here the new parameter, n adjusts the "hardness" of the
924 threshold while M' no longer necessarily corresponds to
925 intrinsic light. [Equations 7, 9 and 10](#) are asymptotically

926 equivalent. The family of curves plotted with blue lines in
927 [Figure 6](#) show R as a function of M using [Equation 10](#), for
928 different values of the parameter n .

929 **Relation to other non-linear transducer models**

930 The three components of the models introduced here are
931 also found in standard non-linear transducer models of the
932 dipper effect (e.g., Foley & Legge, 1981; Nachmias &
933 Sansbury, 1974; Wichmann, 1999): (i) a non-linear relation
934 between stimulus modulation and some internal response, R ;
935 (ii) fixed internal noise added to R ; and (iii) a decision
936 mechanism. The shape of the predicted TvC function is
937 strongly determined by the form of the response function
938 provided the noise that limits the observers' behavior does
939 not precede the nonlinearity (Lasley & Cohn, 1981; Peterson
940 & Birdsall, 1953) and the dipper is typically modeled, as it is
941 here, by assuming a response nonlinearity that is accelerative
942 in the region of M' . In [Equation 10](#), just as in [Equation 7](#),
943 M' is in that sense the "threshold" modulation, even though
944 in [Equation 10](#), a stimulus less than M' can elicit a response,
945 and may be detectable without a pedestal if $w < 1$.
946

947 **The response function and performance contours:** 948 **How hard a threshold?**

949 The two noted shortcomings of the predictions of [Figure 7](#)
950 can be alleviated by assuming a less than ideally-hard
951 threshold through the appropriate choice of n in [Equation 10](#).
952 Softening the assumed threshold nonlinearity in [Equation 10](#)
953 rounds off and slightly elevates the bottom of the dipper, and
954 also increases the predicted separation of the performance
955 contours when the pedestal is sub-threshold or absent. With
956 no pedestal, and small M , the contour spacing in a
957 logarithmic plot is reduced when n is high, since the more
958 accelerated the response function, the less is the change in
959 stimulus modulation needed for a criterion change in
960 response. But for pedestal modulations $M \gg M'$, where
961 Weber's Law applies (at least asymptotically) for any n , the
962 signal modulation must increase the natural log of the total
963 modulation by $\sqrt{2}\sigma_{z_{crit}}$, making the contour spacing wider
964 and independent of n .

965 [Equation 10](#) was used to fit the data for all subjects for
966 the conditions where there was no external noise (assum-
967 ing internal additive noise as before). All three parameters
968 (M' , σ and n) were varied iteratively for a best (least-
969 squares) fit. The best fitting values of n were strikingly
970 high (8, 7, and 5 for HES, AS and GBH, respectively),
971 implying a very abrupt "threshold" nonlinearity. The large
972 values of n that were required to fit the data illustrate the
973 common failure of energy detectors ($n = 2$) to fit data
974 of the sort we obtained (Wichmann, 1999). A value of
975 $n = 2$ generates predictions that are obviously inaccurate
976 (0.14 r.m.s. error in \log_{10} modulation) in two respects: the
977 dipper is clearly too shallow, and the spread between high
978 and low criteria when no pedestal is present is too wide.

979 The exponents and fitting errors for the different
 980 subjects don't differ significantly, and on the basis of the
 981 pooled data the most likely exponent is about 6. But any
 982 value greater than about 3 gives a reasonably good fit to
 983 the data.

986 Data obtained with external noise added

987 A goal of these experiments was to analyze the detection
 988 process by investigating the ability of noise components of
 989 a range of different temporal frequencies to interfere with
 990 detection. To incorporate the effects of noise in our model,
 991 we assume that flicker is encoded as an energy-related
 992 quantity. Thus, information about the frequency and phase
 993 of the flicker is lost. Our limited ability in temporal-
 994 frequency discrimination (Mandler & Makous, 1984)
 995 supports this scenario—at least for relatively high fre-
 996 quencies, which appear as what Roufs and Blommaert
 997 (1981) call 'agitation' (as opposed to the luminance
 998 'swell' visible at lower modulation frequencies).

999 Instead of deriving the flicker energy E from the
 1000 amplitudes of the 200 Fourier components of the stimulus,
 1001 it can be obtained directly as the sum of the squares of the
 1002 time-varying excursion in relative luminance:

$$1003 \Delta L_t / L_{ave} = (L_t - L_{ave}) / L_{ave}, \quad (11)$$

1004 which, by Parseval's Theorem, is proportional to the sum
 1005 of squares of the Fourier component amplitudes. Thus in
 1006 the absence of external noise, E is proportional to the
 1007 square of the signal amplitude, which is half the square of
 1008 the modulation depth M in Equations 7, 9 and 10. Those
 1009 equations can therefore be restated in terms of E/E' instead
 1010 of M/M' , with $E = M^2/2$ and the exponent n replaced by
 1011 $n/2$, so that the best fitting exponent of $n = 6$ becomes
 1012 $n = 3$ thus:

$$1013 R = \log_e([1 + (E/E')^3]^{1/3}). \quad (12)$$

1014
 1015 Whichever way the equation is expressed, the modu-
 1016 lations are squared before the mean or sum is taken, and
 1017 the sum is then subjected (approximately, in the near-
 1018 threshold range, $E \leq E'$) to a power-law (in this case a
 1019 cubic) transform. But precise squaring of the deviations
 1020 before integration is not critical to the predictions of
 1021 energy-detection schemes, so long as the model prevents
 1022 cancellation of positive and negative deviations. The
 1023 energy detector is in this sense representative of a family
 1024 of 'rectified transient' detectors. When only external noise
 1025 has to be considered, all detectors that base decisions on a
 1026 monotonic function of energy perform equivalently
 1027 (Lasley & Cohn, 1981; Peterson & Birdsall, 1953) and
 1028 are effectively energy detectors. But if significant noise is

1029 added after the non-linearity the exponent in Equation 12
 1030 becomes critical. As noted above, linearity with energy
 1031 (an exponent of 2 in Equation 10, or 1 in Equation 12 does
 1032 not yield visually acceptable fits; linearity with modula-
 1033 tion (halving the exponent) is even worse, predicting (in
 1034 the absence of external noise) no dipper at all; but an
 1035 energy detector with cubic response growth (Equation 12)
 1036 gives a good account of our results without external noise.
 1037 We consider next whether the energy-cubed model can
 1038 predict performance with external noise as well.

Simulation methods

1039
 1040 Thresholds in noise were estimated by simulating
 1041 individual trials. The total noise energy E on any trial,
 1042 expressed as a multiple of the expected energy of each
 1043 noise component, is a sample from the chi-square
 1044 distribution with the degrees of freedom equal to the
 1045 number of independent noise components (e.g., 200 for
 1046 the no-notch noise). When a signal or pedestal is present,
 1047 the flicker energy is a sample from the non-central chi-
 1048 square distribution, where the non-centrality parameter is
 1049 the energy due to the sum of pedestal and signal. For each
 1050 simulated presentation, the stimulus energy was generated
 1051 by a random draw from the appropriate distribution, and
 1052 the resulting response was obtained from Equation 12.
 1053 Independent Gaussian internal noise of standard deviation
 1054 σ was then added to the responses for each of the two
 1055 presentations in a simulated 2AFC trial, and the decision
 1056 was counted as correct if the response to the signal
 1057 presentation was greater than to the no-signal presenta-
 1058 tion. We adopted the values for M' and σ that best fit the
 1059 no-noise data for each subject, and a threshold hardness
 1060 exponent $n = 3$ in accordance with Equation 12.
 1061 Simulations were run on a range of test modulations
 1062 spanning the full range of the psychometric function, with
 1063 10000 simulated trials per test modulation per pedestal,
 1064 and the test modulations required for criterion perfor-
 1065 mance were estimated by interpolation. For observers
 1066 GBH, HES and AS, the best-fitting values of M' were
 1067 0.0165, 0.0081 and 0.0226 respectively, and the best-
 1068 fitting values of σ were 0.1761, 0.2314 and 0.1961.

The critical band

1070
 1071 Predictions for thresholds in noise depend on the
 1072 bandwidth over which the noise energy is integrated.
 1073 The simplest energy detector, where all noise frequencies
 1074 are weighted equally, is implausible at the outset, since
 1075 the highest frequencies in the 100-Hz noise band are
 1076 invisible at our mean luminances, and although possibly
 1077 present in neural responses (Hawken, Shapley, & Grosof,
 1078 1996; Lee, Sun, & Zucchini, 2007; Shady, MacLeod, &
 1079 Fisher, 2004), are unlikely to contribute much masking.
 1080 Moreover, the calculated performance assuming full
 1081 sensitivity to all noise frequencies was vastly inferior to

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