Contrast discrimination with pulse trains in pink noise

G. B. Henning

The Sensory Research Unit, The Department of Experimental Psychology, University of Oxford, South Parks Road, Oxford, OX1 3UD, UK

C. M. Bird*

Department of Neuropsychology, The National Hospital, Queen Square, London, WC1N 3BG, UK

F. A. Wichmann

Max-Planck-Institut für biologische Kybernetik, Spemannstrasse 38, D-72076 Tübingen, Germany

Received August 31, 2001; revised manuscript received November 30, 2001; accepted December 13, 2001

Detection performance was measured with sinusoidal and pulse-train gratings. Although the 2.09-cycles-per-degree pulse-train, or line, grating contained at least eight harmonics all at equal contrast, it was no more detectable than its most detectable component. The addition of broadband pink noise designed to equalize the detectability of the components of the pulse train made the pulse train approximately a factor of 4 more detectable than any of its components. However, in contrast-discrimination experiments, with a pedestal or masking grating of the same form and phase as the signal and with 15% contrast, the noise did not affect the discrimination performance of the pulse train relative to that obtained with its sinusoidal components. We discuss the implications of these observations for models of early vision, in particular the implications for possible sources of internal noise. © 2002 Optical Society of America

OCIS codes: 330.1880, 330.5000, 330.5510, 330.7310.

1. INTRODUCTION

Much of our information about spatial vision comes from experiments that involve only low-contrast stimuli, stimuli that are close to their detection thresholds. Contrast-discrimination experiments provide one of the few ways to explore the visual system's response to suprathreshold stimuli. Since the suggestion[1] that early visual processing is accomplished in many relatively independent spatial-frequency and orientation-selective channels, much of the work on contrast discrimination has been performed with sinusoidal gratings and has been aimed at exploring contrast-transduction and gain-control mechanisms operating within single channels.[2–4] The notion of linear and independent channels is probably not viable;[5–9] nevertheless, the multichannel model still captures many aspects of early spatial vision, and, even in nonlinear systems, determination of the linear component of the system usually remains important and interesting. In this paper we report contrast-discrimination experiments using both sinusoidal and multifrequency pulse-train gratings. The experiments explore how information is combined across spatial-frequency channels as well as the mechanisms underlying contrast discrimination within the channels.

One central issue in contrast discrimination is to determine the mechanisms underlying Weber's law. In this paper we introduce a stimulus—the pulse-train grating—that has been used to explore Weber's law at very high contrasts indeed.[10] Here we use the pulse train in a different way.

While most models of contrast discrimination incorporate some source of noise or noise processing, there are major difficulties in determining even the number of different sources of noise, let alone whether Weber's law results from noise of a particular form, from the operation of a nonlinear transducer, or from a combination of the two.[11–13] By exploring the effect of pink noise on detection and on contrast-discrimination performance with pulse trains and with their sinusoidal components, we discern at least two sources of noise and make a preliminary guess at where in the visual processing sequence the noise arises.

Observers in contrast-discrimination experiments are typically required to discriminate between two stimuli that differ only in contrast. When the stimuli are gratings, the grating of lower contrast is often called the "pedestal," and the observers are asked to choose the interval in which a "signal" grating is added to the pedestal. When the signal and pedestal gratings have the same spatial frequency and orientation and are added in phase, the addition of the signal produces only an increase in contrast so that the observers' task can be described either as contrast discrimination or as increment detection; the contrast increment is equal to the contrast of the signal.

One important characteristic of such experiments is

0740-3232/2002/071259-08$15.00

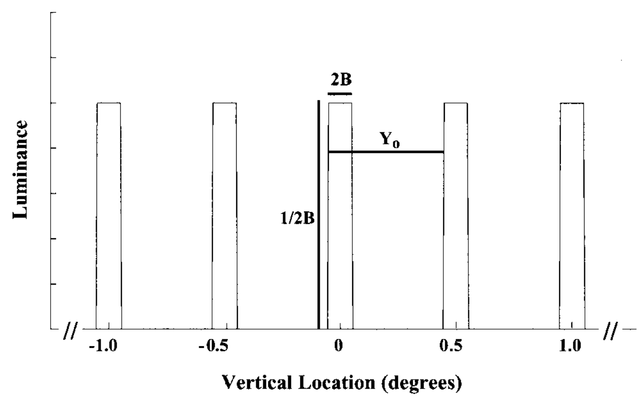

Fig. 1. Luminance of a train of rectangular pulses of width $2B$ and height $1/2B$ shown as a function of distance (degrees of visual angle). The train has a period of Y_0 degrees and a mean luminance of $1/Y_0$. The grating of rectangular pulses approaches an ideal pulse train as B decreases toward zero.

that for certain pedestal contrasts the incremental signal is detected at lower contrasts than with no pedestal at all—the pedestal effect.[9,12,14,15]

In previous contrast-discrimination experiments, we measured contrast discrimination with a number of harmonically related sinusoidal gratings ranging from 2.09 to 16.74 cycles per degree (c/deg).[15] The principal signal in the current detection and contrast-discrimination experiments consisted of a 2.09-c/deg pulse-train, or line, grating.

A pulse train can be described as a periodic repetition of a suitably shaped narrow line. In the limit, as the width of each line is reduced and the luminance of the line increased proportionately, the stimulus approaches an ideal pulse train.[16] An ideal pulse train contains harmonics of all orders at equal contrast. Moreover, the maximum contrast of each harmonic including the fundamental is 200%. Thus a pulse train is a useful stimulus to explore the way in which contrast information, carried in every harmonic, is combined across spatial frequency. Further, the use of pulse trains also allows the study of the pedestal effect to be extended to higher values of contrast than are possible with sinusoidal stimuli. The extension is important in discriminating among different models that have been proposed to explain both contrast discrimination and the pedestal effect.[10,17]

Figure 1 illustrates the cross-sectional luminance profile of a horizontally oriented grating of rectangular pulses, $P_{Y_0}(y)$.

For a given y value, luminance is constant in the horizontal direction. Each horizontal bar of the pulse train has a width in the y direction of 2B and a luminance of $1/2B$. The average luminance is $1/Y_0$. If, for convenience, we assume the grating to be even symmetric, the Fourier series expansion of $P_{Y_0}(y)$ is

$$P_{Y_0}(y) = \frac{a_0}{2} + \sum_{n=1}^{\infty} a_n \cos n\omega_0 y, \tag{1}$$

where

$$\omega_0 = 2\pi/Y_0, \qquad a_n = (2/Y_0)\int_{-Y_0/2}^{Y_0/2} P_{Y_0}(y)\cos n\omega_0 y \mathrm{d}y.$$

Thus for the pulse train,

$$a_n = \frac{1}{BY_0}\int_{-B}^{B} \cos n\omega_0 y \mathrm{d}y = \frac{2}{Y_0}\left[\frac{\sin(n\omega B)}{n\omega B}\right]. \tag{2}$$

When n is zero, a_0 is $2/Y_0$ so the first term in Eq. (1) is seen to be $1/Y_0$, the mean luminance of the stimulus. For all other n, a_n approaches $2/Y_0$ as B approaches zero, so the contrast of the nth component approaches 2.

It is not possible, of course, to produce an ideal pulse train on a CRT. We were limited by our pixel size (~1 arc min of visual angle), by the finite maximum and nonzero minimum luminance of the display, and by the requirement for enough dynamic range to implement the circularly symmetric spatial Hanning window that we used. These constraints force the maximum contrast to depend on the spatial frequency of the pulse train. As an illustration, the cross-sectional luminance profile of an achievable 4.18-c/deg pulse train on the vertically oriented diameter of its Hanning window is shown in Fig. 2(a)

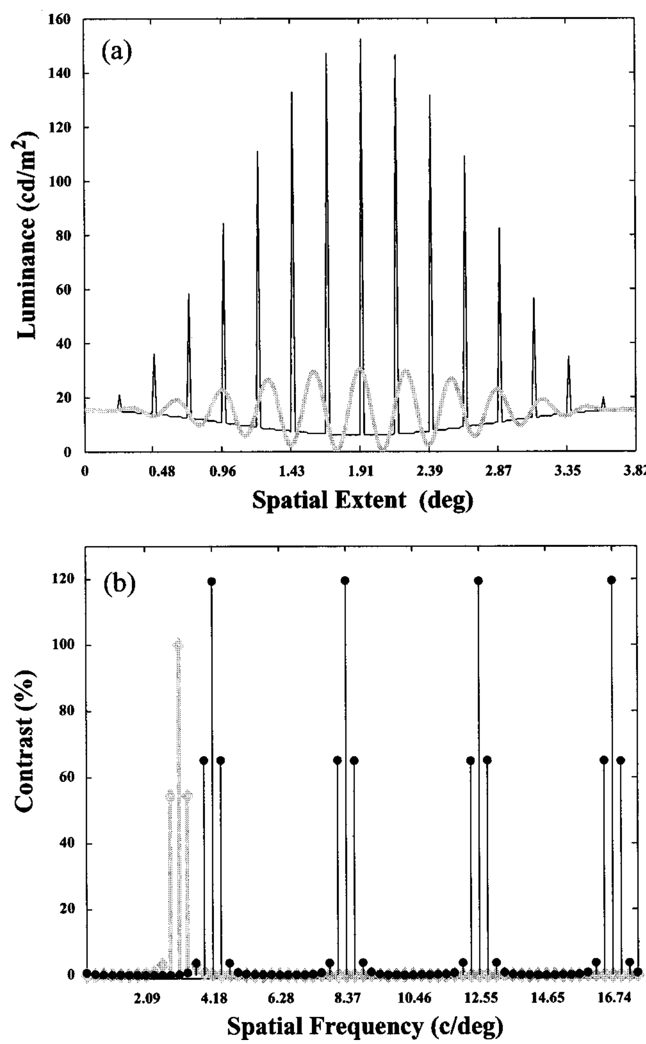

Fig. 2. (a) Cross-sectional luminance profile of a 4.18-c/deg pulse train along a vertical slice through the center of the spatial Hanning window. Luminance (cd/m^2) is plotted as a function of distance (degrees of visual angle). A sinusoidal grating of the same mean luminance, 100% contrast, and slightly lower spatial frequency is shown for comparison. (b) Contrast spectrum of the pulse-train and sinusoidal gratings of (a) as a function of spatial frequency.

together with the profile of a sinusoidal grating with an unachievable contrast of 100% and, for ease of comparison, a slightly lower spatial frequency. The horizontal axis is degrees of visual angle, and the vertical axis is luminance (cd/m^2).

Figure 2(b) gives the amplitude spectrum of both waveforms in units scaled to show contrast. With the 4.18-c/deg pulse train, the contrast of each component reaches 120%. Using a digital camera (Photometrics SenSys 200 KAF 0400) and our 2.09-c/deg pulse train, we measured a maximum of 80% contrast in each of its components up to 16 c/deg. The maximum contrast of a 2.09-c/deg sinusoidal grating of the same mean luminance was 53.2%.

In addition to detection and discrimination experiments with the 2.09-c/deg pulse train, we measured detection and discrimination performance with 2.09- and 8.37-c/deg sinusoids of the same mean luminance as the pulse train.

2. METHODS

Two observers, the authors CMB and GBH, served in different two-alternative forced-choice detection and contrast-discrimination experiments. The stimuli to be detected, the signals, were horizontally orientated pulse-train or sinusoidal gratings. The signals were presented either against uniform fields of the same mean luminance as the signal (10.69 cd/m^2) or against a background grating of the same form, spatial frequency, orientation, and phase as the signal. The background grating (the pedestal) and the signal grating were gated on and off simultaneously inside a rectangular temporal envelope of 78.8-ms duration. Both pedestal and signal had the same circularly symmetric spatial Hanning window with a radius subtending 1.9 deg of visual angle at the viewers' eyes.

The two 78.8-ms observation intervals of each trial were separated by a 750-ms pause. In the detection experiments, a signal grating of a given contrast was presented in one of the two observation intervals, and the observers were required to indicate which interval had contained the signal by pressing buttons during the 1-s answer interval that followed the second observation interval. The signal appeared in the first interval of each trial with probability 0.5. Tones marked the beginning and end of each observation interval, and, after the 1.0-s response interval, tones indicated which interval had contained the signal.

In the discrimination experiments, a pedestal grating of 15% contrast was presented in both observation intervals, and the signal was added in one of the intervals. (The detection experiment is thus just a discrimination experiment with a pedestal of zero contrast.) The addition of the pedestal grating, the signal grating, or their sum did not change the mean luminance of the display (10.69 cd/m^2). We chose the pedestal contrast of 15% because at that contrast, the threshold contrast change is the same for every component of the pulse train at least up to 16.37 c/deg, the highest that we measured.[15]

The phase of the pedestal with respect to the spatial window changed randomly from observation interval to observation interval; one of eight phases (uniformly distributed over 2 π rad) was chosen for each presentation. The phase of the signal, of course, was the same as that of the pedestal so that the signal was always added in the same phase as the pedestal.

The contrasts of both the pedestal and the signal were fixed for blocks of 50 trials, after which the contrast of the signal was changed so that the psychometric functions relating the proportion of correct responses to signal contrast could be determined. The pedestal contrasts (15%, or zero for detection) were chosen in a haphazard order, and the experiments were subsequently repeated in a different order to produce 5- or 6-point psychometric functions with each point based on 100 trials for each pedestal level for each observer. Three-parameter Weibull functions were then fitted to the psychometric functions, and bootstrap-based confidence intervals were obtained for all the fitted parameters as well as for thresholds and slopes.[18,19] The experiments were repeated with sinusoidal gratings of 2.09 and 8.37 c/deg both having the same mean luminance as the pulse train.

The stimuli were generated in MATLAB as floating-point arrays, converted to integer format, and then written to the green gun of a suitably linearized Mitsubishi FR8905SKHKL display. The outputs of three 8-bit digital-to-analog converters were combined through a linear network.[4,20] Stimuli were presented at a frame rate of 152 Hz (with no interleaving), and the linearity of the system was assessed with a digital camera (Photometrics SenSys 200 KAF 0400) to ensure that any distortion introduced by the display was negligible.[4]

All experimental stimuli were presented as a 256 $\times$ 256-pixel array; the central 46% of the display was used. The remaining pixels surrounding the central square were set to the mean luminance. The display was viewed binocularly with natural pupils at a distance of 234 cm so that the central square subtended 3.82 $\times$ 3.82 deg of visual angle at the observers' eyes and each pixel subtended approximately 1 arc min of visual angle.

In Figs. 3–7, the pulse train is indicated by stars, the 2.09-c/deg sinusoidal signal by circles, and the 8.37-c/deg sinusoidal signal by squares. The "super train," described subsequently, is indicated by triangles.

3. RESULTS AND DISCUSSION

Figures 3(a) and 3(b) show psychometric functions for pulse-train detection by the two observers (stars) together with the detection functions for 2.09 sinusoids (circles) and 8.37 sinusoids (squares) of the same mean luminance.

The proportion of correct responses is shown as a function of the contrast of the signal on semilogarithmic coordinates. Each data point for each observer is based on 100 observations obtained from 2 separate blocks of 50 trials.

Contrast for the 2.09-c/deg pulse train is reported in terms of the contrast of its Fourier-series components each of which has the same contrast (at least the eight constituents that we measured up to 16.74 c/deg; the contrast of the pulse train itself is ~0.18 log unit less than that of each of its components). The detection psychometric functions are approximately parallel on these coordinates, and the 2.09-c/deg sinusoidal grating is a factor of 2 or 3 more detectable than the 8.37-c/deg sinusoidal grating. (This is only slightly greater than the ratio measured with the gratings of higher mean luminance[15]; indeed, the eightfold reduction in mean luminance from the previous study had little effect on performance, and thus it seems reasonable to conclude that the form of the contrast-sensitivity function at the lower mean luminance is similar to the monotonic decreasing function of spatial frequency above 2 c/deg that we found earlier.)[15]

Figures 3(a) and 3(b) show that the pulse train, although at least eight components have the same contrast, was slightly less detectable than its most detectable (2.09-c/deg) component for one observer and slightly more detectable for the other. Both effects are small. This is somewhat surprising, as the 4.19-c/deg component of the pulse train is only slightly less detectable than the 2.09-c/deg component,[15] and some improvement in the detectability of the pulse train might have been expected through probability summation.[21–24]

Figures 4(a) and 4(b) show discrimination results for the 2.09-c/deg pulse train (stars) together with those for sinusoidal gratings of 2.09- (circles) and 8.37- (squares) c/deg. In all three cases the contrast of the pedestals was 15%.

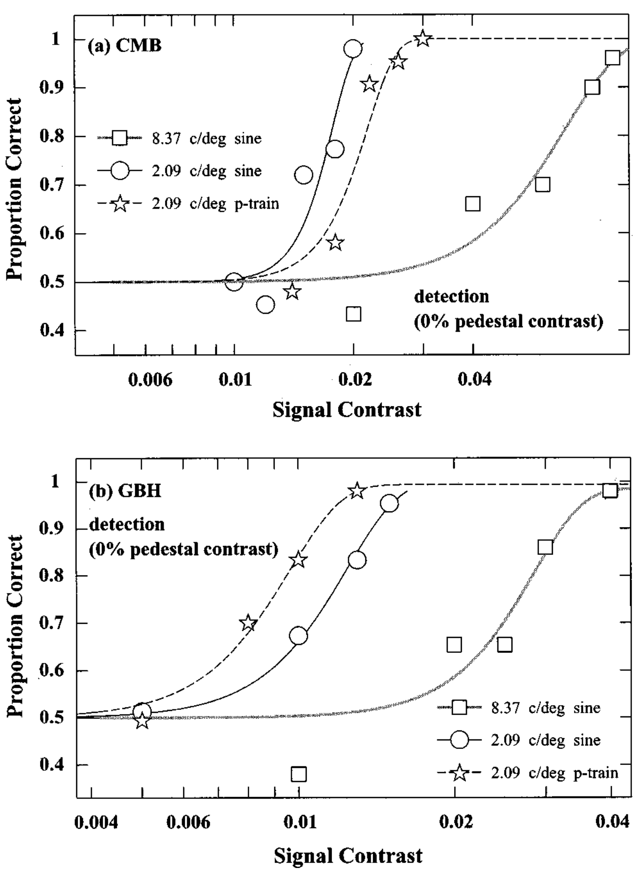

Fig. 3. (a) Proportion of correct responses as a function of signal contrast on semilogarithmic axes. Circles and squares, results for 2.09- and 8.37-c/deg sinusoids, respectively; stars, results for the pulse train. The results are for detection (pedestal contrast of 0%) for observer CMB; each data point is based on 100 observations. Contrasts reported for the pulse train are those of its sinusoidal components. The solid curves are the best (maximum-likelihood) Weibull functions fitted to each data set. (b) As for (a), but for observer GBH.

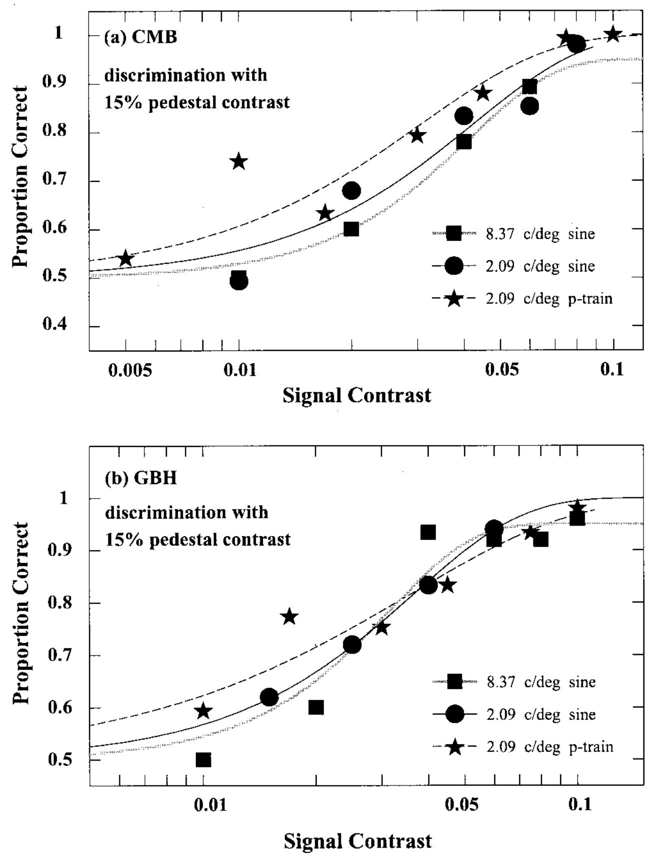

Fig. 4. As for Fig. 3, but for discrimination experiments with a pedestal contrast of 15%.

There is very little difference in the ability of the observers to detect the three signals even though the components of the pulse train, when presented separately at this pedestal contrast, are equally detectable.[15] In spite of there being at least eight equally detectable components, there is no evidence of much probability summation.

There are several possible reasons that the observers were not able to make use of the rich spectral structure of the pulse train. One is that they may be able to inspect only one component at a time, and another is that information available is so highly correlated across components that there is nothing to be gained from their joint consideration. To distinguish between these two possibilities we repeated the experiment, adding visual noise to both observation intervals.

4. SUPPLEMENTARY EXPERIMENT I: PULSE TRAINS WITH NOISE

A. Method

We generated 48 examples of one-dimensional Gaussian noise in which the mean noise-power density of the spatial noise samples was inversely proportional to spatial frequency ("pink" noise). The noise was designed to make the detectability of all the components of the pulse train equal. Since the bandwidths of channels through which individual components are thought to be detected are approximately proportional to frequency, the total mean noise power through the filter centered on any component of the pink noise will be approximately independent of the spatial frequency of the component.[25–27]

The noise was nominally Gaussian in form, and its maximally attainable contrast (limited by the dynamic range of the system used to present the stimuli) was determined empirically. Producing noise with no clipping results in virtually no noise at all, whereas too much clipping at the limits of the 8-bit dynamic range allotted to the noise changes the noise spectrum. (Excessive clipping increases the high-spatial-frequency components of the noise, thus changing the slope of the resulting spectrum.) We simply increased the variance (power) of the noise to find the highest value consistent with the $1/f$ spectral shape that we required. We then calculated the proportion of clipped pixels at the variance that was just consistent with the $1/f$ spectral shape and rejected any noise sample with clipping exceeding that proportion.

The experimental details were identical to the previous experiment save that 16 different noise samples were randomly selected from a set of 48 for each block of 50 trials. One of the 16 noises was then randomly chosen for presentation on each observation interval (the probability that the same noise sample was present in both observation intervals of a single trial was thus $1/16^2$ or $\sim 0.5\%$). The temporal and spatial windowing were the same for the noise, the signal, and the pedestal; the mean luminance of the display was unaffected by the addition of any combination of the three.

Noise fields were interleaved with the fields on which the gratings might be presented. We used one noise field for each of two identical grating (or uniform) fields in order to produce high grating contrasts. The contrast values that we present are appropriately scaled for the three-field frame.

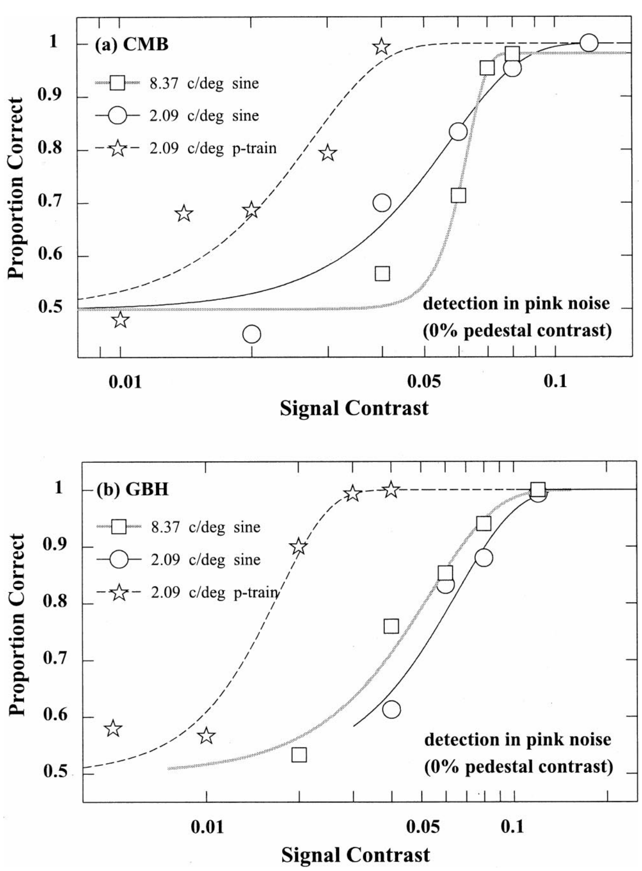

Fig. 5. As for Fig. 3, but the signals were masked by pink noise.

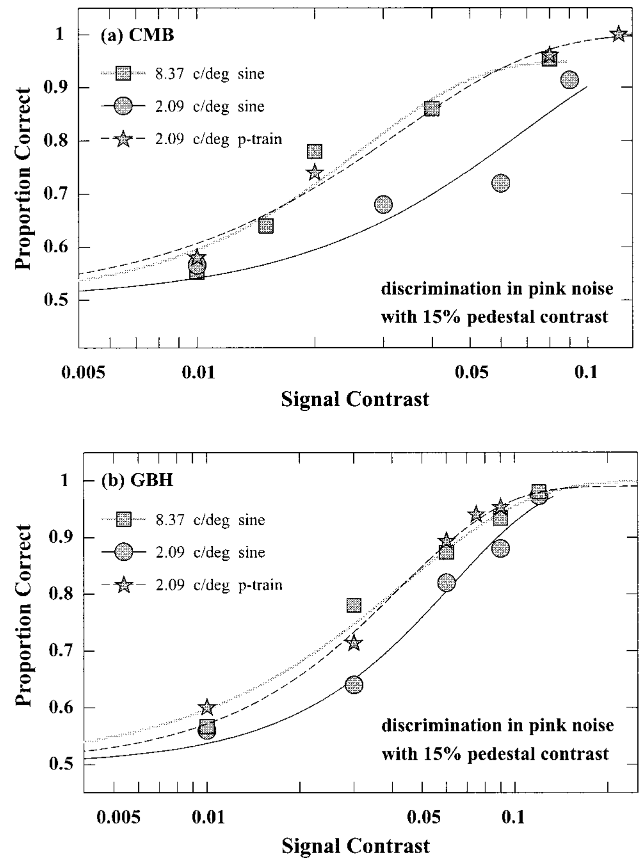

Fig. 6. As for Fig. 5, but for discrimination experiments with a pedestal contrast of 15%.

B. Results and Discussion

Figures 5(a) and 5(b) show detection performance for the 2.09-c/deg pulse train (stars) and for 2.09-c/deg (circles) and 8.37-c/deg (squares) sinusoidal gratings.

The noise affected the detectability of both sinusoidal gratings but by different amounts. The 2.09- and 8.37-c/deg gratings are made approximately equally detectable in the noise. The pulse train, however, is now approximately a factor of 5 more detectable than any of its components.

The implication of this result is that observers are indeed able to derive useful information from the components of the pulse train. The addition of the noise appears to have achieved one or both of two things: By equating the detectability of the components of the pulse train, the noise may have merely made probability summation evident. Alternatively, the noise may have decorrelated the effective masker at different spatial frequencies with the result that independent information about the presence of the pulse-train signal can be derived from different frequency bands, at least when the components fall into separate channels. It is difficult to estimate from the data how many independent sources of information would need to be pooled to produce the difference that we observed[24]; but something like 30, the total number of components in the 60-c/deg bandwidth of the retinal image, is not an unreasonable estimate.

Figures 6(a) and 6(b) show the effect of adding noise to the pulse-train and sinusoidal gratings when the pedestal has 15% contrast.

With this pedestal contrast, unlike in the detection case and even though the components of the pulse train are equally discriminable from their corresponding pedestal components[15] (at least up to 16 c/deg), there is no measurable improvement in the discriminability of the pulse train over that of its components.

5. SUPPLEMENTARY EXPERIMENT II: SUPER TRAINS

A. Method

To resolve the issue of why the addition of noise to the pulse train should produce evidence for probability summation in some cases but not others, we designed a "super train." The super train was produced by summing eight sinusoids with frequencies at every harmonic of 2.09 c/deg up to 16.74 c/deg. The eight components were all added in cosine phase but, unlike the situation with the pulse train in which every component has the same contrast, the components of the super train had contrasts that were adjusted so that at a given super-train contrast, each component would be at its own threshold when viewed separately. We determined the appropriate scaling factor for each component's contrast by fitting exponentials to contrast-sensitivity functions for each observer separately[15] and interpolating for the thresholds of the 6-, 10-, 12-, and 14-c/deg sinusoids.

We used the super train as the signal in a detection experiment without masking noise. The experiment was identical in all other respects to the detection experiments with pulse trains reported as the main result in Section 3.

B. Results and Discussion

Figures 7(a) and 7(b) show the detection results with the super train together with the results from the pulse train and the 2.09-c/deg grating. The contrasts reported for the super train and the pulse train are those of their 2.09-c/deg components. The results are for detection experiments (pedestal contrast of 0%), and each data point is based on 100 observations. Results for 2.09-c/deg sinusoids are shown as circles, and those for the 2.09-c/deg pulse train and the super train are shown as stars and triangles, respectively. For both observers the super train is approximately a factor of 2 more detectable than its components. Such a finding is usually interpreted as evidence for probability summation.

One interesting feature of the data is the slope of the psychometric functions. Testing for the statistical significance of differences in the slopes of psychometric functions is not trivial.[28] However, if a single slope is needed to fit all three functions, then, for observer CMB, the fit to at least one of the functions can always be rejected. Further, the best-fitting common slope to the data sets from the pulse-train and sinusoidal stimuli is rejected as producing a fit to the shallower data from the super pulse.

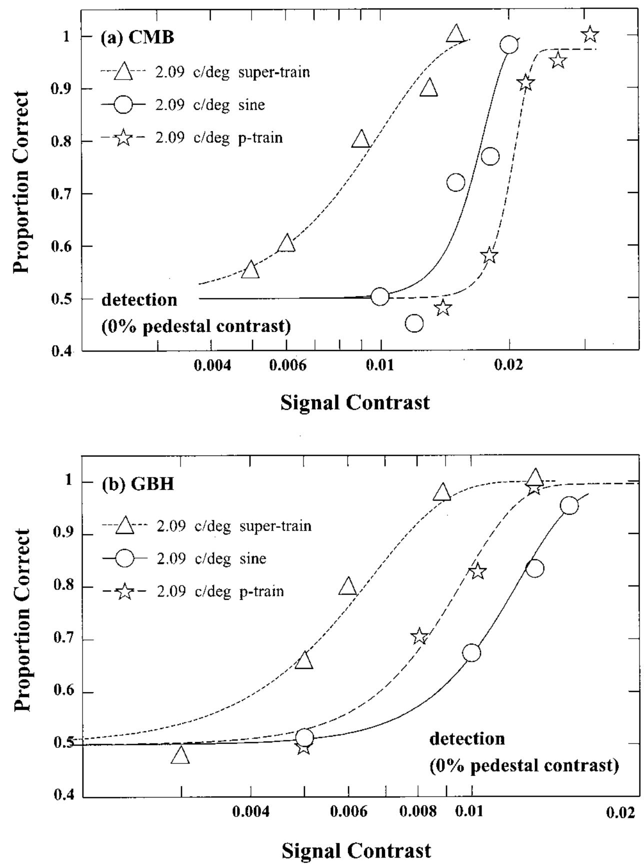

Fig. 7. (a) Proportion of correct responses as a function of signal contrast on semi-logarithmic axes. Circles, results for 2.09-c/deg sinusoids; stars, for the 2.09-c/deg pulse train; triangles, for the super train. The results are for detection experiments (pedestal contrast of 0%) for observer CMB; each data point is based on 100 observations. Contrasts reported for both pulse trains are those of their 2.09-c/deg sinusoidal components. The solid curves are the best (maximum-likelihood) Weibell functions fitted to each data set. (b) As for (a), but for observer GBH.

For GBH, the 95% confidence intervals[18,19,28] for the slope of the best fits to the data sets from the pulse-train and sinusoidal stimuli overlap slightly with the 95% confidence intervals of the (shallower) slope of the data from the super train. Thus we conclude that the slope for the super train is no steeper than for any of its component sinusoids. Such a result is inconsistent with the notion of the observers' using the maximum of several independent indicators of the presence of the signal.

6. GENERAL DISCUSSION

Consider first the detection data (obtained with a pedestal contrast of 0%). The results of supplementary experiment II with the super train make it clear that part of the failure to produce improved performance with the pulse train derives from the unequal detectability of its components; at the contrast at which the 2.09-c/deg component is detectable 75% of the time, no other component appears to have sufficient contrast to make a measurable contribution to detectability. When the components are adjusted to be equally detectable as in the super train, the observers' performance is a factor of 2 better than with any of its components viewed singly. This improvement is usually attributed to probability summation,[21] but the finding that the slopes of the psychometric functions obtained with the super pulse are no steeper than those with any of its sinusoidal components is difficult to reconcile with that interpretation, whether the observers average the decision statistic across channels[24] or compare maxima across channels in the two observation intervals.[29]

The addition of pink noise in supplementary experiment I also has the effect of equating the detectability of the components—this time the components of the pulse train. In the noise, the detectability of the pulse train improves over that of its components by approximately a factor of 5. That is more than a factor of 2 larger than the improvement produced by equating detectability with the super train. The additional improvement may arise because the external noise, in addition to making the components of the pulse train equally detectable, also decorrelates the factors that make each component hard to detect. Improvement through probability summation is greatest when the noises limiting detection in each channel are independent (or if not independent, at least largely uncorrelated). If, in the absence of external noise, the limiting factor in each channel were some form of common "internal noise" identical in all channels, there would be no improvement from using more than one of the channels. In this case, the decorrelating effect of our external noise would be expected to produce improved detection performance with the pulse train relative to its sinusoidal components by making the noise that limits the detectability of each component less correlated across channels.

Unlike in the detection case, adding noise when the pedestal had 15% contrast had no effect on the contrast-discrimination performance of the pulse train relative to that of its components. Although at 15% pedestal contrast the contrast increments in each component are equally discriminable when the components are viewed separately, no improvement was measured when the components were combined in the pulse train. The implication is that once the pedestal contrast raises the grating contrast above the masking noise, the information in different frequency bands is too highly correlated to produce improvement through probability summation.

The "internal noise" in question might just be that signal-level-dependent noise measured neurally[30–32] or the internal noise often assumed to be responsible for Weber's law in psychophysical models of contrast discrimination in vision or amplitude discrimination in hearing. It is sometimes just assumed that such a noise exists.[33] But it would perhaps be more interesting to determine its source. In hearing, it has been suggested that variability in the center frequency of the auditory filter provides the internal noise.[34] Although this is also possible in vision, it seems unlikely that the variability in all the channels would be as highly correlated as the failure to find improvement in discrimination implies. One possibility is that eye movements (or their equivalent) introduce highly correlated variability relative to the different spatial weighting functions that produce the channels' spatial-frequency tuning. This explanation too seems unreasonable in that a given variability in space will be an increasing fraction of the spatial weighting function as spatial frequency increases. (This is because the bandwidth of spatial-frequency channels increases with spatial frequency, and consequently the extent of the corresponding spatial weighting function decreases with increasing frequency.) One further possibility is that with pedestal contrasts above 10% or so, the common internal noise factor might arise early in the system in the form of a (noisy) gain-control mechanism operating before the formation of the channels.[35]

We should note that our interpretation of the results is inconsistent with the interpretation of a recent paper[36] in which it is argued that contrast discrimination is limited by a transducer nonlinearity and an internal noise of almost constant magnitude.

ACKNOWLEDGMENTS

We are grateful to J. Nachmias for his criticism of an earlier version of this paper. The research was carried out in the Sensory Research Unit, Oxford University, and was supported by grants from the Wellcome Trust to G. B. Henning and F. A. Wichmann and by a Fellowship by Examination at Magdalen College, Oxford University (F. A. Wichmann).

*Present address, The Institute of Cognitive Neuroscience, London WC1N 3AR, UK.

REFERENCES

1. F. W. Campbell and J. G. Robson, "Application of Fourier analysis to the visibility of gratings," J. Physiol. (London) **197**, 551–566 (1968).
2. J. Nachmias and R. V. Sansbury, "Grating contrast: discrimination may be better than detection," Vision Res. **14**, 1039–1042 (1974).
3. G. E. Legge and J. M. Foley, "Contrast masking in human vision," J. Opt. Soc. Am. **70**, 1458–1471 (1980).
4. F. A. Wichmann, "Some aspects of modelling human spatial vision: contrast discrimination," D. Phil. dissertation (Oxford University, Oxford, UK, 1999).
5. G. B. Henning, B. G. Hertz, and D. E. Broadbent, "Some experiments bearing on the hypothesis that the visual system analyzes patterns in independent bands of spatial frequency," Vision Res. **15**, 887–899 (1975).
6. A. M. Derrington and G. B. Henning, "Some observations on the masking effects of two-dimensional stimuli," Vision Res. **29**, 241–246 (1989).
7. F. A. Wichmann and D. J. Tollin, "Masking by plaid patterns is not explained by adaptation, simple contrast gain-control or distortion products," Invest. Ophthalmol. Visual Sci. **38**, S631 (1997).
8. F. A. Wichmann, "Plaid maskers revisited: asymmetric plaids," in *Visuelle Wahrnehmung. Beiträge zur 3. Tübinger Wahrnehmungskonferenz*, H. H. Bülthoff, M. Fahle, K. R. Gegenfurtner, and H. A. Mallot, eds. (Knirsch Verlag, Kirchentellinsfurt, Germany, 2001), Vol. 3, p. 57.
9. F. A. Wichmann and G. B. Henning, "Implications of the pedestal effect for models of contrast-processing and gain-control," presented at the 1999 OSA Annual Meeting, September 26–October 1, Santa Clara, Calif.
10. G. B. Henning and F. A. Wichmann, "Pedestal effects with periodic pulse trains," Perception **28** (Suppl.), S137 (1999).
11. J. Yang and W. Makous, "Zero frequency masking and a model of contrast sensitivity," Vision Res. **35**, 1965–1978 (1995).
12. J. Yang and W. Makous, "Modelling pedestal experiments

with amplitude instead of contrast," Vision Res. **35**, 1979–1989 (1995).

13. W. Makous, "Fourier models and the loci of adaptation," J. Opt. Soc. Am. A **14**, 2323–2345 (1997).
14. F. A. Wichmann, G. B. Henning, and A. Ploghaus, "Nonlinearities and the pedestal effect," Perception **27** (Suppl.), S86 (1998).
15. C. M. Bird, G. B. Henning, and F. A. Wichmann, "Contrast discrimination with sinusoidal gratings of different spatial frequency," J. Opt. Soc. Am. A **19**, 1267–1273 (2002).
16. A. Papoulis, *The Fourier Integral and Its Applications* (McGraw-Hill, New York, 1962).
17. F. A. Wichmann and G. B. Henning, "Contrast discrimination using periodic pulse trains," in *Visuelle Wahrnehmung. Beiträge zur 3. Tübinger Wahrnehmungskonferenz*, H. H. Bülthoff, M. Fahle, K. R. Gegenfurtner, and H. A. Mallot, eds. (Knirsch Verlag, Kirchentellinsfurt, Germany, 2000), p. 74.
18. F. A. Wichmann and N. J. Hill, "The psychometric function I: fitting, sampling and goodness-of-fit," Percept. Psychophys. **63**, 1293–1313 (2001).
19. F. A. Wichmann and N. J. Hill, "The psychometric function II: bootstrap based confidence intervals and sampling," Percept. Psychophys. **63**, 1314–1329 (2001).
20. D. G. Pelli and L. Zhang, "Accurate control of contrast on microcomputer displays," Vision Res. **31**, 1337–1350 (1991).
21. N. Graham and J. Nachmias, "Detection of grating patterns containing two spatial frequencies: a comparison of single and multichannel models," Vision Res. **11**, 251–259 (1971).
22. N. Graham, "Visual detection of aperiodic spatial stimuli by probability summation among narrowband channels," Vision Res. **17**, 637–652 (1977).
23. J. G. Robson and N. Graham, "Probability summation and regional variation in contrast sensitivity across the visual field," Vision Res. **21**, 409–418 (1981).
24. C. W. Tyler and C.-C. Chen, "Signal detection theory in the 2AFC paradigm: attention, channel uncertainty and probability summation," Vision Res. **40**, 3121–3144 (2000).
25. C. Blakemore and F. W. Campbell, "On the existence of neurons in the human visual system selective to the orientation and size of retinal images," J. Physiol. (London) **203**, 237–260 (1969).
26. C. Stromeyer and B. Julesz, "Spatial frequency masking in vision: critical bands and spread of masking," J. Opt. Soc. Am. **62**, 1221–1232 (1972).
27. G. B. Henning, B. G. Hertz, and J. L. Hinton, "Effects of different hypothetical detection mechanisms on the shape of spatial-frequency filters inferred from masking experiments: I. Noise masks," J. Opt. Soc. Am. **71**, 574–581 (1981).
28. N. J. Hill, "Testing hypotheses about psychometric functions: an investigation of some confidence-interval methods, their accuracy, and their use in evaluating optimal sampling strategies,"D. Phil. dissertation (Oxford University, Oxford, UK, 2001).
29. G. B. Henning, "A model for auditory discrimination and detection," J. Acoust. Soc. Am. **42**, 1325–1334 (1967).
30. A. F. Dean, "The variability of discharge of simple cells in the cat striate cortex," Exp. Brain Res. **44**, 437–440 (1981).
31. M.-N. Shadlen, K.-H. Britten, W.-T. Newsome, and J. A. Movshon, "A computational analysis of the relationship between neuronal and behavioral responses to visual motion," J. Neurosci. **16**, 1486–1510 (1996).
32. W. S. Geisler and D. G. Albrecht, "Visual cortex neurons in monkeys and cats: detection, discrimination, and identification," Visual Neurosci. **14**, 897–919 (1997).
33. D. M. Green and J. A. Swets, *Signal Detection Theory and Psychophysics* (Wiley, New York, 1966).
34. G. B. Henning, "Amplitude discrimination in noise, pedestal experiments, and additivity of masking," J. Acoust. Soc. Am. **45**, 426–435 (1969).
35. G. B. Henning, R. W. Millar, and N. J. Hill, "The detection of incremental and decremental bars at different locations across Mach bands and related stimuli," J. Opt. Soc. Am. A **17**, 1147–1159 (2000).
36. A. Gorea and D. Sagi, "Disentangling signal from noise in visual contrast discrimination," Nature Neurosci. **4**, 1146–1150 (2001).