# Masking effect produced by Mach bands on the detection of narrow bars of random polarity

**G. B. Henning, K. T. Hoddinott, and Z. J. Wilson-Smith**

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

**N. J. Hill**

*The Max-Planck-Institut für Biologische Kybernetik, Tübingen, Germany*

Received January 6, 2004; revised manuscript received March 23, 2004; accepted March 29, 2004

Difficulties arise in measuring masking by Mach bands because very-low-contrast signals distort the bands. [J. Opt. Soc. Am. A **17**, 1147 (2000).] Adding narrow luminance increments (bright bars) in the dark Mach band widens the dark band; adding decrements (dark bars) narrows the dark band, and conversely in the bright bands. Randomizing signal polarity prevents observers from using the distortion of the Mach bands as a cue to the presence of the signal. We measured (two-alternative–forced-choice) Mach bands' masking of randomly selected bright (incremental) or dark (decremental) bars. Detection was worse in both dark and bright Mach bands than on the neighboring plateaus. Separate analysis of trials containing only one polarity signal revealed 9-cycle/deg oscillations in performance as a function of location. Oscillations in the two polarities were approximately 180° out of phase. © 2004 Optical Society of America

*OCIS codes:* 330.1880, 330.5000, 330.5510, 330.7310.

## 1. INTRODUCTION

Mach bands are regions of light and dark, not present in the stimulus, but arising from the visual system's response to certain spatial distributions of luminance.[1,2] Studying Mach bands should therefore provide insight into spatial vision. Pessoa provides an excellent and extensive examination of the many plausible models of mechanisms that might cause Mach bands.[3] One major obstacle to our understanding Mach bands has been the difficulty of measuring them.[2,4–7] The masking effects they produce provide one indirect approach to their quantification.[6,7] However, one difficulty in masking experiments is that even very small perturbing signals near Mach bands change their appearance[7,8]: Luminance increments near the center of the dark Mach band broaden the band and decrements narrow it.[7] The opposite effects occur in the bright Mach band where increments narrow the band and decrements widen it.

Our first experiment measured these changes, which were observed in two-alternative-forced-choice detection experiments. In one study, for example,[7] the distortion of the Mach bands was apparent to the observers before the signal bars could otherwise be detected, with the consequence that when stimuli were presented in blocks of fixed polarity, observers were able to detect a signal presented near a Mach band by observing the effect of the signal on the shape of the band. Observers trying to detect a luminance increment in a dark Mach band could sometimes identify the interval containing the incremental signal as the interval in which the dark Mach band appeared a little wider. Observers could not achieve 100% correct performance using the cues from the distorted Mach bands because the effect is tiny with very small increments and becomes irrelevant once the contrast at which the signal bars become occasionally visible as such is reached. At that contrast, the observers reported switching cues and using the more reliable one—"seeing a signal bar." Nevertheless, the use of the additional cue at low signal levels distorts the psychometric functions relating the proportion of correct responses to the magnitude of the signal by producing, relative to measurements from regions remote from the Mach bands, large improvements in performance below about 75% correct.[7] This distortion obscures the underlying masking function.

In the two-alternative-forced-choice experiments reported here, we sought to avoid the distortion of the psychometric functions by randomizing the polarity of the bars to be detected. The observers reported that randomization made the opposing small effects of the signal bars on the appearance of the Mach bands uninformative: an incremental signal in the dark Mach band would cause the dark Mach band to widen slightly but a decremental signal would cause the band to narrow slightly. Thus the observer, not knowing the polarity of the signal, could not use the width of the Mach band to determine the interval containing the signal. For the naïve observer (KTH) who began the experiments with random polarity signals, the width of the bands was never a consistent cue. The experienced observer (GBH) found that, because the effects of the low-contrast, just-detectable signals on the widths of the bands are so small, he was unable to use the potential cue provided by deviations of the appearance of the bands from their appearance in the absence of any signal. The similarity of the observers' results is consistent with

1084-7529/2004/081379-09$15.00 

this interpretation. Further, the randomization of the signal polarity removed the distortions of the psychometric functions previously reported.[7]

We began with a preliminary experiment to measure the effect of probe signals of different polarity and magnitude on the appearance of Mach bands.

## 2. GENERAL METHODS

Let us call the stimulus used to generate the Mach bands the "masking" stimulus. The masking stimulus was uniform in the horizontal direction inside a $4° \times 4°$ region of an otherwise dark monitor subtending $6.8° \times 5.5°$ at the viewing distance of 200 cm. (One line of the display subtended 0.9375′ of visual angle.) Within the $4° \times 4°$ region, the luminance of the masking stimulus changed only in the vertical direction. The vertically orientated cross-sectional profile of the $4° \times 4°$ masking stimulus comprised a horizontally orientated dark plateau of 40.25 $cd/m^2$ subtending $4° \times 1.33°$ at the top of the display, a 114.75 $cd/m^2$ bright plateau also subtending $4° \times 1.33°$ but at the bottom of the display, and a linear luminance ramp (subtending $4° \times 1.33°$) linking the plateaus. The ramp modulation that comprised the masking stimulus was constant along vertical slices through the display. Luminance was measured with a Gamma Scientific photometric telescope calibrated against a beta radiation source. When the masking stimulus was not presented, the $4° \times 4°$ stimulus region had the uniform mean luminance of 78 $cd/m^2$.

The display was generated in a Mitsubishi Electric FR8905SKHKL color monitor driven at a frame rate of 98 Hz with no interleaving. The monitor was carefully linearized and the stimuli produced by connecting two independent, 8-bit digital-to-analog converters of a NuVista frame store through a passive attenuator to the "green" gun of the display.[9,7] In this experiment, the two digital-to-analog converters were combined in a ratio of 7 to 1 to achieve approximately 12-bit precision in the linearized image. The dynamic range was assessed by taking digital images of the display, analyzing the spectral content of the measured image, and comparing the results of that analysis with a similar analysis of the numerical representation of the desired image subject to various degrees of rounding.

## 3. PRELIMINARY EXPERIMENT: WIDTHS OF MACH BANDS

### A. Introduction

In the preliminary experiment, we first attempted to locate the center and edges of the Mach bands generated by the masking stimulus. Observers adjusted arrows at the sides of the masking stimulus to indicate the locations of the center and edges of the Mach bands. Then we added either incremental or decremental bars at the center of one or the other Mach band and repeated the measurements to determine the effects of bars of different magnitude and polarity on the widths of the bands.

### B. Methods

Three observers (TC, GBH, and ZW-S), the latter two of whom are authors, participated in the experiment. The masking stimulus was used to generate Mach bands and the observers were asked to adjust the vertical position of two inwardly pointing dim red arrows, horizontally aligned on the sides of the masking stimulus in order to locate the top, bottom, or center of the Mach bands. Each measurement of each position was repeated six times by each observer for both dark and bright Mach bands. The center of each band was taken as the mean of six settings with no added bar. The widths of the bands for all conditions were taken as the difference between the mean of six settings for the top of the Mach band and the mean of six settings for the bottom.

The masking stimulus was repeatedly presented in the following cycle chosen to match that of the main experiment: a 400-ms presentation followed by an 800-ms pause, a second 400-ms presentation, and an 1800-ms pause. During the pauses the stimulus field had the uniform 78-$cd/m^2$ mean luminance.

The shafts of the arrows were produced using the "red" gun of the display and were clearly visible for the duration of each 400-ms presentation of the masking stimulus. The arrows appeared in a random position at the start of each trial and were adjusted up or down in coarse or fine steps by pressing buttons on a keypad. The observers were given unlimited time to make their adjustments and were merely instructed which band was of interest and whether they were to align the arrows with the top, center, or bottom of the band. When satisfied with the arrows' position, the observer pressed another button to record the chosen location. A new random starting location for the arrows was then assigned and a new measurement begun.

Once the location of each observer's bright and dark bands had been determined, probe stimuli of different magnitude and polarity were added at their centers. The probe stimuli were either incremental or decremental bars that were added to a single horizontal line of the Mach-band-generating stimulus and thus subtended $\approx 0.9'$ of visual angle vertically and extended horizontally across the 4° of the display. The magnitude and sign of the probe stimuli were fixed for a block of trials in which the observers adjusted the vertical position of the red arrows and several different probe magnitudes were used in pseudorandom order.

### C. Results

Graphs showing the width of the Mach bands (in arcminutes) against the magnitude of the probe stimuli ($cd/m^2$) are presented for probes in the dark Mach band [Fig. 1(a)] and for probes in the bright Mach band [Fig. 1(b)]. (The error bars indicate $\pm 1$ standard deviation.) For the dark band, when no probe stimulus was present (0-magnitude probe), the band subtended about 9′ for each observer. However, as Ratliff *et al.*[8] also observed, there were considerable interobserver differences in the widths of the bright Mach bands [Fig. 1(b)]. The variability seen from the size of the error bars reflects the precision with with the edges of the bands can be located.

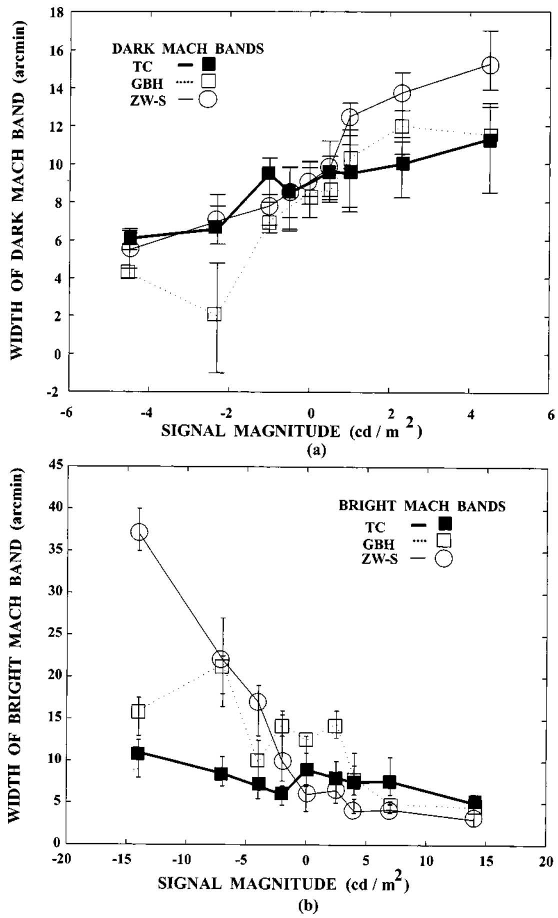



Fig. 1. For three different observers, the widths of (a) dark and (b) bright Mach bands as a function of the magnitude of a narrow bar added in the center of each observer's dark Mach band. (Note the difference in scale on the ordinates of the figures.) Zero magnitude indicates no bar, positive values indicate incremental bars, negative values, decremental bars. The error bars show ±1 standard deviation of six measurements.

### D. Discussion

The preliminary experiment quantifies the effect on the widths of Mach bands produced by narrow probes at their centers. As previously observed,[7] both increments and decrements affect the subjective appearance of the bands. Although there is considerable variability in the effect of increasing the magnitude of the probe, the trend for each observer is the same: for dark bands, the greater the magnitude of the stimulus increment, the wider the band appears. When the probe stimulus is a luminance decrement, increasing the probe magnitude narrows the dark band. The opposite effect was found in bright bands: decrements of increasing magnitude widen the band, while increments of increasing magnitude narrow it.

The results are not in agreement with those of Ratliff *et al.*,[8] who found that the addition of a bar always narrows the band, and that the effect depends only on the probe's contrast and not on its polarity. The difference in the findings may be a result of differences in the location of the bars and differences in the duration for which the Mach-band stimuli were presented.[10]

At the 400-ms duration of our stimuli, the observers reported that the bright band appeared about the same width but less distinct than the dark band, with the consequence that the bright band's edges were harder to determine and the error bars consequently larger. The nearly equal widths of the dark and bright bands is unlike the asymmetry usually reported under continuous viewing conditions in which the bright band usually appears wider than the dark band. When a probe stimulus widened a band, the band became yet more diffuse and its edges yet more difficult to distinguish. All observers reported that large decrements made the bright band especially difficult to detect, and the variability in the measured size of the bright Mach band presented with large added decrements is consequently high.

For incremental or decremental bars of magnitude greater than $\approx 3$ cd/m$^2$, the observers reported that the bars themselves become visible. Nonetheless, increasing the magnitude of the bars continues to increase their effect on the width of the Mach bands. Below magnitudes of $\approx 3$ cd/m$^2$, the bars themselves are not visible and it is in this region where observers previously reported using the widths of the bands as a cue to the presence of a signal.[7] At such low magnitudes, the changes in width of the Mach bands are small, thus accounting for observers' failure to obtain much more than 75% correct responses using the cue and for the difficulty of even noticing the width changes other than in the context of forced-choice experiments.

The effect of the signals—or probes—on the width of the bands can be understood as a consequence of locally operating gain-control mechanisms much as Mach hypothesized more than a century ago. Mach's single "on-center" weighting function needs to be replaced by (at least) two weighting functions: one class, "on-center," with excitatory centers and inhibitory surrounds possibly mediating the responses that produce the bright Mach band, the other class, "off-center," with inhibitory centers and excitatory surrounds possibly mediating the responses that produce the dark Mach band.[7,11–13] The probes affect the gain of the mechanisms they stimulate over an extended area, as Mach postulated, and to an extent that depends on the polarity and magnitude of the probe. The result is the variation in the width of the bands that we have measured.[7]

One practical implication of the opposing effects of incremental and decremental signal bars is that changes in the appearance of the bands that result from the presence of low-contrast probes can be prevented from becoming cues to the interval containing the signal. By randomizing the polarity of the signal, trial by trial, so that the observers do not know what polarity bar they are trying to detect, we can make changes in the appearance of the bands of no use to the observers.

## 4. DETECTION EXPERIMENT: MASKING EFFECTS OF MACH BANDS

### A. Introduction

The nearly opposite effects produced by incremental and decremental bars on the appearance of Mach bands provided a technique for making the effect of the bars on the Mach bands of no use to observers trying to detect the bars. By randomizing the polarity of the bars to be detected, the opposing small effects on the appearance of the

Mach bands were made uninformative: depending on the polarity of the signal, either the wider or the narrower band could have been caused by the signal. Thus randomizing the polarity of the signals makes the appearance of the Mach bands of no help in determining which interval contained the signal. Moreover, the observer who knew the differential effect of the two types of signal on the appearance of the bands was unable, because the effects are so small with probes near their thresholds, to memorize the appearance of the bands in the absence of any signal and thus use deviations from that appearance as a cue to the presence of either type of signal.

### B. Methods

Two of the authors (KTH and GBH) were required to detect horizontally orientated "signal" bars in standard two alternative-forced-choice experiments. The signals subtended 0.9′ of arc vertically at the viewing distance of 200 cm and extended horizontally across the 4° width of the display. The masking stimulus that generated Mach bands was gated on and off rectangularly in time in both 400-ms observation intervals. In one of the observation intervals of each trial, either a luminance increment or a luminance decrement—the signal to be detected—was gated on and off simultaneously with the masking stimulus. The observation intervals were separated in time by 800 ms. The magnitude and location of the signal was fixed for blocks of 55 trials, but the polarity of the signal was randomly chosen on each trial such that the probability of an increment was 0.5. There was always a signal in one of the observation intervals and the probability that the first observation interval held the signal was 0.5 on each trial and independent of the signal's polarity. After the observers pressed one of two buttons to indicate the interval they thought to have contained the signal, they were informed which interval had contained the signal but they were not informed of its polarity. Except for the two 400-ms observation intervals of each trial, the luminance of the $4° \times 4°$ stimulus region remained uniform at 78 cd/m$^2$.

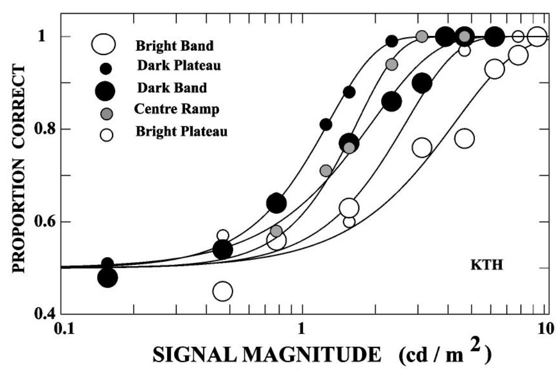
The spatial location of the (potential) signal was indicated to the observers in both observation intervals by inward pointing arrows on each side of display. The arrows were generated by the red gun of the display, and the horizontal shafts of the arrows persisted for the duration of each observation interval. The arrows were also present during a 600-ms warning interval that preceded the first observation interval by 200 ms. During each observation interval, the red gun also generated faint numerals located beside the arrows to indicate the observation interval. Before trials began, the observers viewed the uniform field in a dim background for a few minutes' adaptation.

The magnitude of the signal was constant for blocks of 55 trials, the first five of which served as practice, and was then changed in order to derive 5 or 6 point psychometric functions with at least one performance level above 90% correct and one below 60% correct. The location of the signal was then changed and the process repeated. Finally, the entire experiment was repeated with locations taken in reverse order thus producing psychometric functions of five or six points each based on 100 observations per point for each observer.

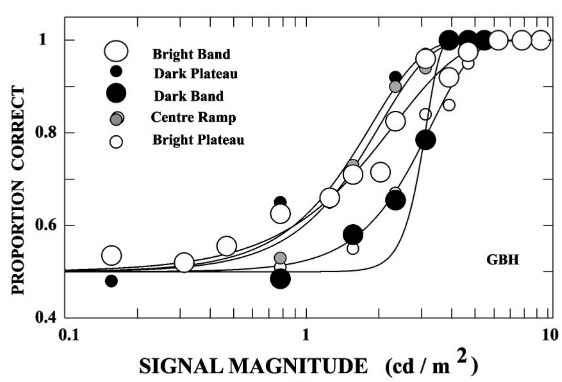
Although the observers were not informed of the polarity of the signals, the results from trials on which increments were presented could be analyzed separately from those on which decrements were presented.

### C. Results and Discussion

Figures 2(a) and 2(b) show some psychometric functions relating the proportion of correct responses (linear scale) to the absolute value of the signal (cd/m$^2$, logarithmic scale). Results for KTH are shown in the upper panel, those for GBH in the lower. The different sizes of the data points serve merely to differentiate the stimulus conditions; each point is based on 100 observations for each observer detecting a signal of random polarity having the magnitude shown on the abscissa. The proportion correct is taken across the randomly chosen polarities. Psychometric functions from the centers of the bright and dark plateaus are shown together with functions from locations within the bright and dark Mach bands and from the center of the luminance ramp. No psychometric function had the unusual shape found with fixed polarity signals,[7] and the psychometric functions for both observers appear roughly parallel on these coordinates.




(a)




(b)

Fig. 2. Proportion of correct detection for a narrow bar presented at various locations on a Mach-band-producing stimulus as a function of the magnitude of the luminance change (cd/m$^2$) on semilogarithmic coordinates. The signal to be detected was a bar with a randomly selected luminance increment or decrement. The curves are maximum-likelihood fits to the Weibull function,[14,15] and the size of the symbols is chosen merely to help distinguish the data sets. Each point is based on 100 judgments from a single observer: (a) KTH, (b) GBH.

We tested the hypothesis that the psychometric functions were parallel on semilogarithmic coordinates separately for each observer, using the bootstrap technique and code from Wichmann and Hill[14,15]: first, three-parameter Weibull functions were fitted to each psychometric function for all the stimulus locations we used, and the signal magnitudes corresponding to 75% correct responses—the "thresholds"—from the best (maximum likelihood) fitting functions were determined. Second, the magnitude of the signal levels entering into each psychometric function were divided by the threshold contrast so that the thresholds became 1. Third, the scaled psychometric functions were combined into a single data set, the best three-parameter Weibull function was fitted to that set, and its slope on semilogarithmic coordinates at 75% correct responses was extracted. The slopes, change in proportion correct per unit change in log absolute target luminance (cd/m$^2$), for the two observers differed only slightly: 1.70 for KTH, 1.97 for GBH. Finally the individual psychometric functions were refitted, fixing the parameter of the Weibull function that determines slope at the value that gave the slope of the best fit to the combined data set. In no case did fixing the slope significantly affect the correlation between the error in each fit and location on the psychometric function.[14,15] Consequently the effect of location on the masking pattern for our data can be represented by a single performance level. We chose the conventional level corresponding to 75% correct.

Figures 3(a) and 3(b) show the signal magnitude corresponding to 75% correct responses (cd/m$^2$, logarithmic scale) for the random polarity signals as a function of location (linear—degrees of visual angle measured from the top of the masking stimulus). The dark Mach band appeared at the beginning of the ramp near 1.33° (indicated by the filled rectangle below the *x* axis) and the bright Mach band at the end of the ramp near 2.67° (indicated by the open rectangle below the *x* axis). Figure 3(a) shows the results for KTH, Fig. 3(b), for GBH. The error bars around each point are nonparametric estimates of the 68% confidence interval (±1 standard deviation) derived using the bootstrap technique.[14,15] More masking was produced near the bright and dark Mach bands than on the neighboring plateaus.

This result, predicted by the model explored by Henning *et al.*[7] and Henning[13] appeared in their data but was somewhat obscured by distortions of their psychometric functions arising from their signals' perturbation of the Mach bands. Removing that cue by randomizing the signal polarity appears to allow the masking effect to be seen. The threshold elevation produced in the dark Mach band relative to performance on the uniform field of the dark plateau (approximately 0.16 log units for KTH, approximately 0.29 log unit for GBH) is smaller than the threshold elevation produced by the bright Mach band relative to performance on the uniform field of the bright plateau (approximately 0.22 log unit for KTH, approximately 0.47 log unit for GBH).

The small elevation factors result, in part, from the shallow ramp we used in order to be able to explore masking near the bands in fine spatial detail; experiments at a limited number of locations on a Mach-band-producing

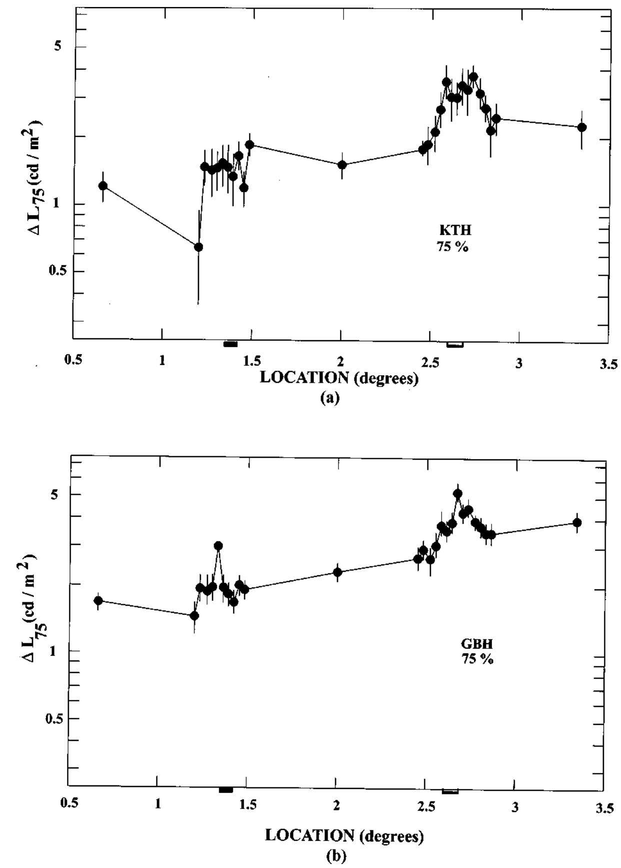



Fig. 3. Magnitude of the luminance change (cd/m$^2$) corresponding to 75% correct detection as a function of the distance from the top of the masking stimulus to the location of the signal to be detected on semilogarithmic coordinates. The signal was a narrow, randomly selected, luminance increment or decrement. The error bars show the 68% confidence intervals (±1 standard deviation). (a) Data for KTH, (b) for GBH. The rectangles below each abscissa mark the approximate location and extent of the Mach bands produced by the masking stimulus: the filled rectangle for the dark band, the open rectangle for the bright band.

stimulus with twice the slope of the ramp gave an average elevation factor for the dark band of 0.40 log unit and that for the bright band of approximately 0.46 log unit: With four times the slope, the elevation factors rose to approximately 0.44 and approximately 0.56 log unit for the dark and bright bands, respectively.

KTH requires smaller signals to obtain 75% correct than GBH. We explored the difference using the Weber fraction of the observers obtained in a further supplementary experiment in which the backgrounds during each observation interval consisted of uniform fields with luminances that ranged from 8 to 140 cd/m$^2$. We performed the supplementary experiments to determine if Weber's law held at background luminances that produced thresholds that corresponded to our masked thresholds. We wanted to be sure that our measurements were all derived, in effect, from luminance regions governed by Weber's law.

The supplementary experiment was identical to the experiment using Mach-band backgrounds except that the plateaux of the Mach-band-generating stimulus were replaced by uniform fields having the mean luminance of the display (78 cd/m$^2$). The ramp was replaced by a uniform field with luminances that varied over the course of the experiment from about 10 to about 135 cd/m$^2$. The central 1.33° region was gated on and off for each of the 400-ms observation intervals, and the signal to be detected was again a bar of randomly chosen polarity always centered in the region.

Figures 4(a) and 4(b) show the results of the supplementary experiment. The figures show the magnitude of the luminance change required for 75%-correct performance divided by the luminance of the uniform background as a function of the luminance of the uniform background. The vertical lines show the 68%-confidence intervals. The range of luminances includes the values for the dark and bright plateaus [40–115 cd/m$^2$]. Over this range of luminance, the magnitude of the signal corresponding to 75%-correct responses was approximately proportional to luminance. Further, the approximate proportionality included the levels of increments and decrements corresponding to the 75%-correct thresholds in either the dark or bright band. The geometric mean of the proportionality constant—the Weber fraction—was 0.025 for KTH and 0.032 for GBH. The ratio of the observers' Weber fractions is 0.78 and when the data of

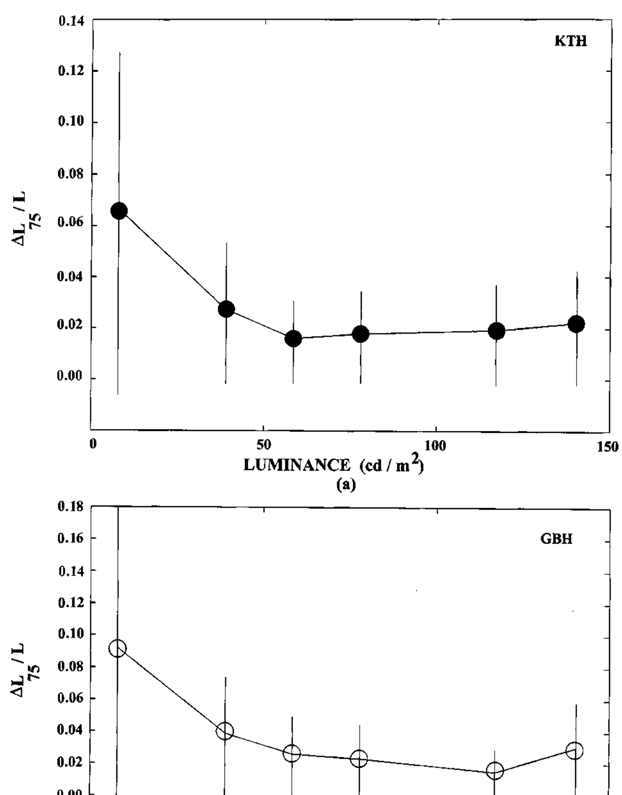



Fig. 4. Ratio of the magnitude of the luminance change corresponding to 75% correct detection to the uniform background luminance as a function of the background luminance (cd/m$^2$) on linear coordinates. Both the background and the random polarity bars to be detected were turned on for 400 ms with rapid onset and offset. The error bars show the 68% confidence intervals (±1 standard deviation). (a) Data for KTH, (b) for GBH.

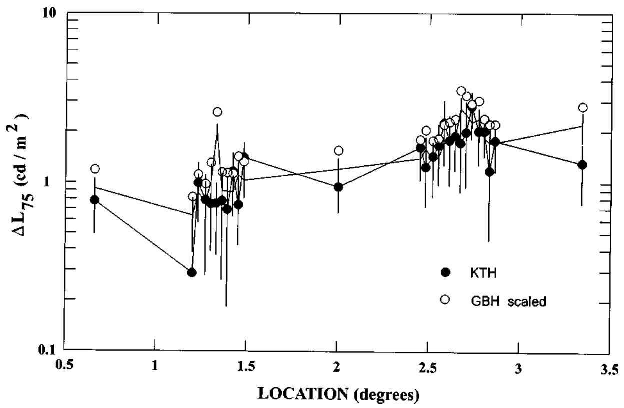



Fig. 5. Magnitude of the luminance change (cd/m$^2$) corresponding to 75% correct detection as a function of location of the random-polarity signal on semilogarithmic coordinates. For clarity, only the error bars for KTH showing ±1 standard deviation are given. Data for GBH scaled by the ratio of the Weber fraction of the two observers are shown as open symbols.

GBH are scaled by this factor, the observers' results are approximately superimposed.

The dark Mach band, of course, appears darker than the dark plateau. Consequently the question arises whether our approximation to Weber's law extends into the effective luminance region of the dark Mach band. Our only test was to note the magnitude of the signal required to produce 75% correct performance when the signal was centered in the dark band, to search for a luminance value in the supplementary experiment that required the same magnitude signal, and to see whether Weber's law extended to that luminance level. It did.

### D. Results and Discussion (Continued)

Figure 5 shows the results for KTH (closed symbols) together with the results of GBH scaled down by the ratio of the observers' Weber fractions (open symbols). Signal magnitudes (logarithmic scale) for 75% correct are shown as a function of location. The figure illustrates that differences in the observers' performance were principally determined by the difference in their Weber fractions.

Our results show that in the regions in and around the Mach bands, performance changes in ways very different from that predicted by Weber's law based either on luminance or on brightness. The results, at least when averaged across the two conditions of signal polarity, are consistent with the predictions of one extension of the Naka–Rushton equation in which the normalizing luminance is derived from an extended region.[7,16] Detection performance is worse in the vicinity of both the bright *and* dark Mach bands than on the neighboring plateaux. The reason that the model predicts the difficulty the observers experience in detecting the signals near dark and bright Mach bands is that the dark and bright bands travel in different "channels": bright bands in channels driven by on-center cells and dark bands in channels driven by off-center cells.[7,11,12] In the model, the Mach-band stimulus drives up the response in the on-center channel near the bright Mach band, and Weber's law, which the model exhibits, means that larger changes are needed to detect the signal. The Mach-band stimulus also drives up the response near the dark Mach band but in the off-center channel, and the operation of Weber's law in that channel means that larger changes are again needed to detect the signal near the dark Mach bands.

While the model captures many aspects of the pooled data, there are important features that it fails to capture when the data for increments and decrements are separately analyzed.

### E. Increments and Decrements Separately

Although the polarity of the signal was randomly chosen on each trial and not known to the observers, the results for each condition were separately analyzed into those arising from trials with increments and those arising from trials with decrements. Figures 6(a) and 6(b) show separately for each observer the magnitude of increments corresponding to 75% correct responses divided by the background luminance, and Figs. 7(a) and 7(b) show the magnitude of decrements corresponding to 75% correct also divided by the background luminance. In each figure the threshold signal level (cd/m$^2$) is shown against location. The vertical lines show the 68% confidence intervals for each point.

The striking feature of both figures is the large variation in performance with location. Each data point is based on approximately half the number of trials as the combined data of Fig. 3, reflected by the increased range of the 68% confidence interval. But the oscillations in performance are much larger than the confidence intervals. Both observers show the oscillations, and for both observers the oscillations with increments are very nearly 180° out of phase with the oscillations produced by the decrements.

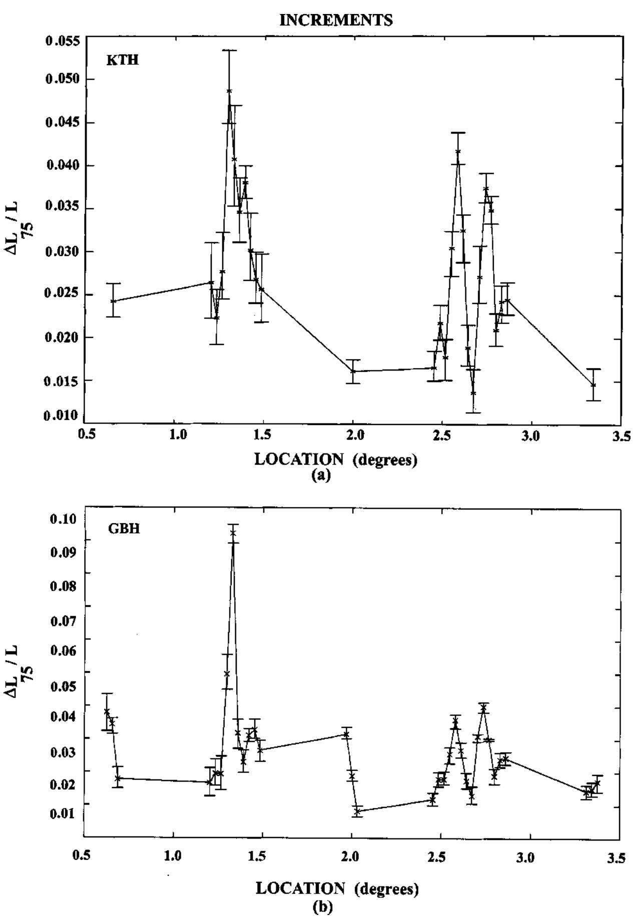



Fig. 6. Ratio of the luminance increment corresponding to 75% correct detection to the background luminance as a function of the location of the signal across the Mach-band-generating stimulus on linear coordinates. Although gathered with random-polarity signals, only the data for incremental signals are shown. The error bars show ±1 standard deviation. (a) Data for KTH, (b) for GBH.

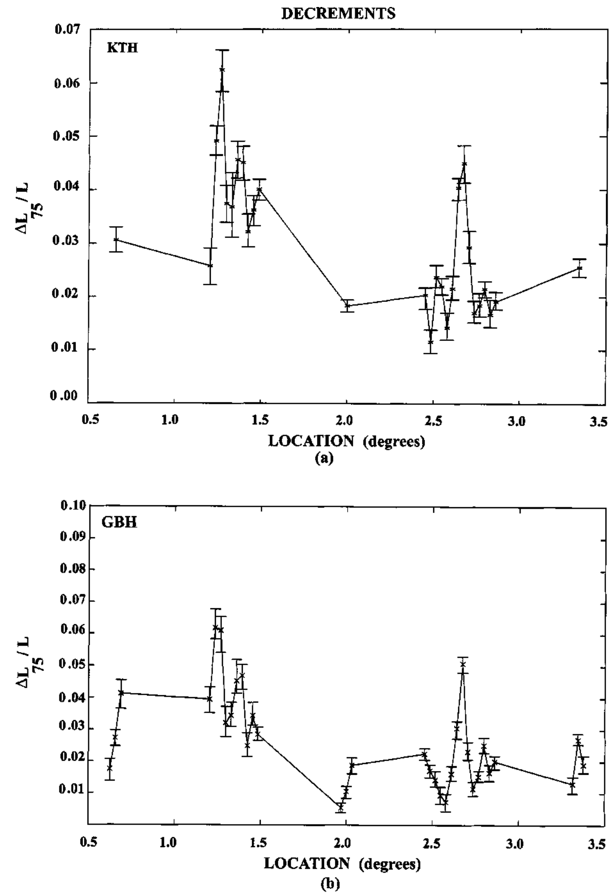



Fig. 7. Ratio of the magnitude of the luminance decrement corresponding to 75% correct detection to the background luminance as a function of the location of the signal across the Mach-band-generating stimulus on linear coordinates. Although gathered with random polarity signals, only the data for decremental signals are shown. The error bars show ±1 standard deviation. (a) Data for KTH, (b) for GBH.

It is difficult to determine the spatial frequency of the oscillation because its extent is limited and its magnitude changing. Both factors necessarily broaden the band of frequencies generated by the oscillation and make its frequency indeterminate. Our best estimates, from maxima in the cross correlation of sections of the measured oscillation with sinusoids of different frequency and phase, suggest that it is about 9.3 cycles/deg for KTH and 8.6 cycles/deg for GBH.

## 5. GENERAL DISCUSSION

The oscillations of Figs. 6 and 7 are not predicted by the modified Naka–Rushton equation because it does not predict the spatial-frequency-tuned channels found in cortical cells and psychophysically.[17–24] Spatial-frequency tuning is usually measured in the spatial-frequency domain, and it is not a straightforward matter to determine which of many possible spatial weighting functions to associate with a given spatial-frequency selectivity.[13,25,26] Spatial-frequency tuning is crude, at least by auditory standards, but the associated spatial weighting functions show some oscillations at the center frequency of the channel. The oscillations are of alternating regions in which excitatory and inhibitory effects are expected to occur, and the oscillations in the data of Figs. 6 and 7 may reflect the operation of a spatial-frequency-tuned channel operating after the mechanisms characterized by the modified Naka–Rushton equation.[3,7,16]

To see how the ripples might arise, recall that the location of the luminance change that the observers were attempting to detect was indicated by arrows at the side of the screen. Presumably, the observers align their foveae on that implied line whatever its location on the masking background. For locations moving closer and closer to the ramp but still on a plateau, the low-amplitude oscillations might reflect the sequence in which excitatory and inhibitory regions of the observers' weighting function fell under the ramp.

The fact that the oscillations for increments and decrements, although they have the same spatial frequency, are 180° out of phase suggests that increments and decrements are detected in different channels: if increments are detected in off-center channels, then decrements would be detected in on-center channels having the same-shaped weighting function with the sign of the corresponding lobes reversed. This observation is inconsistent with the notion that dark and bright Mach bands travel in separate on- and -off-center-driven channels,[7,11,12] and it might be better just to imagine cortical cells with the appropriate spatial weighting characteristic.[26]

The question then arises why the observers should have chosen to use channels tuned to such high spatial frequencies. After all, we are more sensitive to sinusoidal gratings somewhere nearer 3 cycles/deg[27,28] than the 8- or 9-cycle/deg channels suggested by the oscillations of Figs. 6 and 7. To see why the observers might have used such high-frequency channels recall that the signal they were attempting to detect was a narrow line. The spatial-frequency spectrum of a narrow line is very broad and has significant energy density over the entire range of spatial-frequencies to which the visual system responds. If the observers base their decisions on something like the filtered energy output of a channel,[25,29,30] then the channel with the highest ratio of signal-to-masker energy in its output should give the best detection of the line. The masking stimulus, like the signal, has a continuous energy-density spectrum. However, unlike the signal, which has an energy density that is approximately constant over the range of visible spatial frequencies, the masking stimulus has an energy density that falls as $1/f^2$. Thus channels with high spatial frequency are favored because they will have a higher signal-to-masker ratio in their output. High spatial-frequency channels are also favored because the bandwidth of a channel on linear coordinates increases roughly in proportion to frequency,[18,19,20] thus channels with high spatial frequencies "see" more of the signal. However, the sensitivity of a channel decreases above some relatively low spatial frequency determined by the temporal frequency of the stimulus and its mean luminance.[27,28,31] Thus that the observers operate near 8 cycles/deg seems to reflect a compromise between the increase in bandwidth and signal-to-masker ratio and the decrease in sensitivity as the channels' center frequencies increase. It remains to be seen what operations, if any, can modify the channels used by the observers.

## ACKNOWLEDGMENTS

This research, supported by the Wellcome Trust, was based in part on an undergraduate thesis of K. T. Hoddinott.[32] We are grateful to T. Curnow for her criticism of earlier versions of this paper.

## REFERENCES

1. E. Mach, *Uber die Wirkung der raumlichen Verteilung des Lichtreizes auf die Netzhaut* F. Ratliff, ed., translated in Ref. 2 (Holden-Day, San Francisco, Calif., 1965).
2. F. Ratliff, *Mach Bands: Quantitative Studies on Neural Networks in the Retina* (Holden-Day, San Francisco, Calif., 1965).
3. L. Pessoa, "Mach bands: How many models are possible? Recent experimental findings and modeling attempts," Vision Res. **36**, 3205–3227 (1996).
4. E. M. Lowry and J. J. DePalma, "Sine-wave response of the visual system. I. The Mach phenomenon," J. Opt. Soc. Am. **51**, 740–746 (1961).
5. J. J. DePalma and E. M. Lowry, "Sine-wave response of the visual system. II. Sine-wave and square-wave contrast sensitivity," J. Opt. Soc. Am. **52**, 328–335 (1962).
6. A. Fiorentini, M. Jeanne, and G. Toraldo di Francia, "Mésures photometriques visuelles sur un champ à gradient d'éclairement variable," Opt. Acta **1**, 192–193 (1955).
7. G. B. Henning, R. W. Millar, and N. J. Hill, "Detection of incremental and decremental bars at different locations across Mach bands and related stimuli," J. Opt. Soc. Am. A **17**, 1147–1159 (2000).
8. F. Ratliff, N. Milkman, and N. Rennert, "Attenuation of Mach bands by adjacent stimuli," in Proc. Natl. Acad. Sci. USA **80**, 4554–4558 (1983).
9. D. Pelli and L. Zhang, "Accurate control of contrast on microcomputer displays," Vision Res. **31**, 1337–1350 (1991).
10. S. Novak and G. Sperling, "Visual threshold near a continuously visible or a briefly presented light-dark boundary," Opt. Acta **10**, 187–191 (1963).
11. I. Fine, "Mach bands," undergraduate thesis (Oxford University, Oxford, UK, 1993).
12. J. Nachmias, "Contrast modulated maskers: test of a late nonlinearity hypothesis," Vision Res. **29**, 137–142 (1989).
13. G. B. Henning, "Masking effects of low-frequency sinusoidal gratings on the detection of contrast modulation in high-frequency carriers," J. Opt. Soc. Am. A **21**, 486–490 (2004).
14. F. A. Wichmann and N. J. Hill, "The psychometric function I: fitting, sampling and goodness-of-fit," Percept. Psychophys. **63**, 1293–1313 (2001).
15. F. A. Wichmann and N. J. Hill, "The psychometric function II: bootstrap-based confidence intervals and sampling," Percept. Psychophys. **63**, 1314–1329 (2001).
16. P. Kortum and W. S. Geisler, "Adaptation mechanisms in spatial vision II. Flash thresholds and background adaptation," Vision Res. **35**, 1595–1609 (1995).
17. F. W. Campbell and J. G. Robson, "Applications of Fourier analysis to the visibility of gratings," J. Physiol. (London) **197**, 551–566 (1968).

18. C. Blakemore and F. W. Campbell, "Adaptation to spatial stimuli," J. Physiol. (London) **200**, 11P–13P (1969).
19. G. B. Henning, B. G. Hertz, and J. Hinton, "Effect of different hypothetical detection mechanisms on the shape of spatial-frequency filters inferred from masking experiments: noise masks," J. Opt. Soc. Am. **71**, 574–581 (1981).
20. G. B. Henning, "Spatial-frequency tuning as a function of temporal frequency and stimulus motion," J. Opt. Soc. Am. A **5**, 1362–1373 (1988).
21. C. Enroth-Cugell and J. G. Robson, "The contrast sensitivity of retinal ganglion cells of the cat," J. Physiol. (London) **258**, 517–552 (1966).
22. R. L. DeValois, R. E. Yund, and N. Hepler, "The orientation and direction selectivity of cells in macaque visual cortex," Vision Res. **22**, 531–544 (1982).
23. R. L. DeValois, D. G. Albrecht, and L. G. Thorell, "Spatial-frequency selective cells in macaque visual cortex," Vision Res. **22**, 545–559 (1982).
24. W. S. Geisler and D. G. Albrecht, "Bayesian analysis of identification performance in monkey visual cortex: nonlinear mechanisms and stimulus certainty," Vision Res. **35**, 2723–2730 (1995).
25. G. B. Henning, A. M. Derrington, and B. C. Madden, "Detectability of several ideal spatial patterns," J. Opt. Soc. Am. **73**, 851–854 (1983).
26. D. B. Hamilton, D. G. Albrecht, and W. S. Geisler, "Visual cortical receptive fields in monkey and cat: spatial and temporal phase transfer function," Vision Res. **29**, 1285–1308 (1989).
27. J. G. Robson, "Spatial and temporal contrast-sensitivity functions of the visual system," J. Opt. Soc. Am. **56**, 1141–1142 (1966).
28. D. H. Kelly, "Flickering patterns and lateral inhibition," J. Opt. Soc. Am. **59**, 1361–1370 (1969).
29. B. E. Carter and G. B. Henning, "The detection of gratings in narrow-band visual noise," J. Physiol. (London) **219**, 355–365 (1971).
30. C. R. Carlson and R. W. Klopfenstein, "Spatial-frequency model for hyperacuity," J. Opt. Soc. Am. A **2**, 1747–1751 (1985).
31. 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).
32. K. T. Hoddinott, "The detection of incremental and decremental bars presented at different locations across the Mach band stimulus," undergraduate thesis (Oxford University Oxford, UK, 2000).