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CONTRAST CONSTANCY: DEBLURRING IN HUMAN VISION BY SPATIAL FREQUENCY CHANNELS

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SUMMARY

1. The perception of contrast was measured in humans by a technique of subjective contrast-matching, and was compared with contrast sensitivity as defined by threshold measures.

2. Contrast-matching between different spatial frequencies was performed correctly (especially at frequencies above 5 c/deg) despite the attenuation by optical and neural factors which cause large differences in contrast thresholds.

3. Contrast-matching between single lines of different widths was also veridical, and was not limited by the spatial integration (Ricco's Law) present at threshold. Adaptation to gratings altered the appearance of lines, and this could be best understood in Fourier terms.

4. The generality of these results was shown by matching the contrast of pictures which had been filtered so that each contained a one octave band of spatial frequencies.

5. Within the limits imposed by threshold and resolution, contrast-matching was largely independent of luminance and position on the retina.

6. Six out of eleven astigmatic observers showed considerable supra-threshold compensation for their orientation-specific neural deficit in contrast sensitivity.

7. These results define a new property of vision: contrast constancy. It is argued that spatial frequency channels in the visual cortex are organized to compensate for earlier attenuation. This achieves a dramatic 'deblurring' of the image, and optimizes the clarity of vision.

INTRODUCTION

Over the past twenty years the use of sinusoidal gratings has added enormously to our understanding of visual processes. The contrast sensitivity function (c.s. function) measures sensitivity to gratings of different spatial frequencies, where sensitivity is defined as the reciprocal of the contrast threshold. The shape of this function and the way it alters with changes in viewing conditions allow strong inferences to be made about the underlying physiological processes.

The drop in sensitivity at high spatial frequencies can be attributed to blurring from two main sources: the optical limitations of the eye and spatial summation in the nervous system. Campbell & Green (1965) elegantly dissociated these two factors experimentally, and quantified their relative contributions to the over-all c.s. function. The fall-off at low spatial frequencies is usually attributed to lateral inhibition (Cornsweet, 1970), but there may be a small effect due to the decreasing number of cycles present in the display (see Estévez & Cavonius, 1975). At low luminances and in peripheral vision there is a drop in absolute sensitivity, as well as a shift of the c.s. function to lower spatial frequencies (Campbell & Green, 1965; Daitch & Green, 1969; Hilz & Cavonius, 1974). This is consistent with the idea that the visual system has a coarser 'grain' and larger receptive fields under these conditions.

At threshold, however, one is measuring the limits of visibility rather than the normal operating characteristic. It is by no means clear that the c.s. function can be taken as a modulation transfer function (m.t. function) for normal suprathreshold vision. It follows that the shape of the c.s. function under different viewing conditions will not necessarily predict the quality of vision under these conditions.

In our experiments we have used a contrast-matching technique to assess the fidelity of suprathreshold vision, and to compare it with contrast sensitivity as defined by the contrast threshold. We have studied apparent contrast at different spatial frequencies, in foveal and peripheral vision, in photopic and scotopic conditions, and at different orientations in astigmatic subjects.

A general finding is that two patterns will match in apparent contrast when their physical contrasts are equal, despite gross differences in the contrast thresholds for the two patterns. Apparent contrast is to a large extent independent of the contrast sensitivity function. Visual information is blurred by optical and neural processes (which determine the shape of the c.s. function) but is evidently restored by an active process of compensation. The result may be termed 'contrast constancy'. We shall argue in detail below that contrast constancy may be mediated by the system of cortical channels selective for orientation and spatial frequency, which has been amply demonstrated in man (Campbell & Robson, 1968; Blakemore & Campbell, 1969; Campbell & Maffei, 1970; Kulikowski & King-Smith, 1973).

METHODS

Two patterns, usually sinusoidal gratings, were presented side-by-side on oscilloscope screens using the television technique of Campbell & Green (1965) which we have previously described (Sullivan, Georgeson & Oatley, 1972). Both patterns were vertical and had a mean luminance of 10 cd/m^2 except where stated. The contrast of one of the patterns (the 'variable') was controlled by the observer by means of a logarithmic potentiometer; the contrast of the other (the 'standard') was set by the experimenter. The observer's task was to adjust the variable until it matched the standard in apparent contrast. We were careful to stress the significance of the term contrast. Observers made judgements by comparing the brightness differences within each pattern. Over a wide variety of experimental conditions most observers found this reasonably easy to do; the judgement accorded with what is commonly understood by contrast. A particular concern was that the observers should not be misled into matching the patterns according to some impression of 'visibility'. As our results will show, it is often the case that when the subjective contrast of two patterns match, one pattern may be very much easier to see than the other. It was made clear to the observers that they were not to be worried by this paradox and were only to pay attention to contrast.

RESULTS

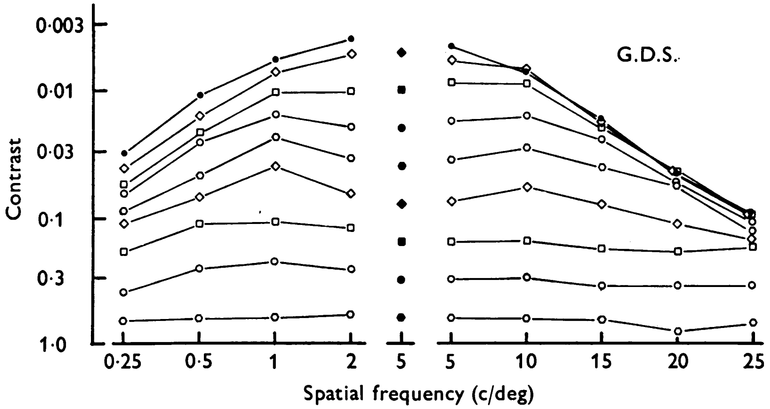
1. The apparent contrast of sinusoidal gratings

Observers made matches between a grating of 5 c/deg (the standard) and a grating of a different frequency (the variable).

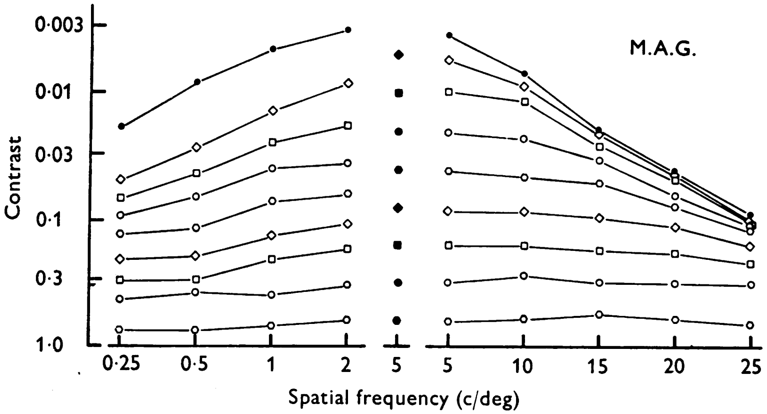
The experiment was carried out under two viewing conditions. For variable gratings of high frequency (5, 10, 15, 20 and 25 c/deg) the viewing distance was 229 cm and the screens subtended 2 deg, separated horizontally by a gap of 1·5 deg. With low frequency variable gratings (2, 1, 0·5 and 0·25 c/deg) the viewing distance was reduced to 57 cm and the screens subtended 8 deg, separated by 6 deg. Viewing was monocular, with the preferred eye, and the head was supported by a bite-bar. No artificial pupil was used, and the observer was allowed to look back and forth at the two gratings as he wished.

In all, each observer made eight matches of contrast for each pair of gratings during a series of four experimental sessions. Within each session the frequency of the variable was kept fixed and a range of contrasts of the standard was presented in either ascending or descending order. Threshold settings were also taken in each session. The standard was presented equally often on the left- and right-hand screens.

The results have been plotted in Text-figs. 1 and 2 as equal-contrast contours, analogous to the equal-loudness contours of audiometry. The observers were the two authors, but in all essential respects the results have been confirmed with observers who were unaware of the purpose of the work and had little previous experience of grating patterns. The asymmetrical shape of the c.s. function makes it more appropriate to plot the high frequency results on a linear axis of frequency, while the low frequency results are on a log axis. Each datum of Text-figs. 1 and 2 represents the mean logarithm of eight settings of the variable grating. The uppermost curve (filled circles) is the contrast sensitivity function. Sensitivity is optimal around 5 c/deg, and falls off steeply at higher frequencies, being about 1 log unit worse at 20 c/deg. There is a similar drop in sensitivity at lower frequencies.



Text-fig. 1. Apparent contrast of sinusoidal gratings. The unconnected symbols show the contrast of the standard (5 c/deg) grating. The corresponding open symbols show the contrast of the variable grating which matches the standard in perceived contrast. Contrast sensitivity is shown by the connected filled circles. Observer G.D.S.



Text-fig. 2. Apparent contrast of sinusoidal gratings. As Text-fig. 1. Observer M.A.G.

The unconnected filled symbols represent the standard contrasts used. The settings of the variable which matched the standard in apparent contrast are shown by the corresponding open symbols. If the standard and the variable gratings appeared to match when their contrasts were physically matched, then the equal-contrast curves would be horizontal lines through each filled symbol. The results for both observers showed that this was indeed the case when the standard was of fairly high contrast. This is very marked for the high frequency part of the Figures but is less impressive at low frequencies. At lower contrast levels, the equal-contrast curves tended to converge on to the c.s. function at high spatial frequencies. The observers had some difficulty in making these matches because high frequency gratings seem to have high contrast as soon as they are above threshold. This is a paradox mentioned earlier: at threshold a high frequency grating is barely visible, yet may appear to be of higher contrast than the standard, which is easy to see.

These results are in broad agreement with previous measurements of the apparent contrast of sinusoidal gratings. Watanabe, Mori, Nagata & Hiwatashi (1968), and Blakemore, Muncey & Ridley (1973) have reported experiments essentially similar to our own, and obtained very similar results. Both these studies found that the equal-contrast curves became progressively flatter at higher contrasts, although the effect was not quite as pronounced as that reported here. This may be due to the contradiction between apparent contrast and visibility. Unless attention is drawn explicitly to the *contrast* in the pattern it is very tempting for the observer to set the two gratings to be equally 'striking', and make artificially high settings near threshold.

Bryngdahl (1966) and Davidson (1968) have also measured apparent contrast, but results were obtained only at low spatial frequencies (0·3–8·5 c/deg). Out of all these studies, only one (Davidson's) failed to show a marked flattening of the curves at higher contrasts. This is probably because the contrasts used by Davidson were less than 1 log unit above threshold.

It is clear from the low frequency half of Text-figs. 1 and 2 that flattening occurs only at substantially higher contrasts. In comparison the effect at high spatial frequencies is more rapid and complete and occurs at contrast levels much closer to threshold. In the remainder of this paper we will mainly be concerned with this higher frequency region.

Contrast constancy by means of spatial frequency compensation

The results of the first experiment show that a high frequency sinusoidal grating is seen as having an apparent contrast corresponding to its physical contrast despite a strong reduction in visual sensitivity at threshold. These findings are surprising when the causes of the loss of sensitivity are considered. An important contributing factor is optical blur which progressively reduces the physical contrast of the retinal image as frequency increases. Measurements of the eye's optics have shown that under viewing conditions comparable to our own only 10–15% of the object contrast of a 25 c/deg grating is transmitted to the retina (Campbell & Gubisch, 1966). The optics act linearly so that for a given spatial frequency the contrast transmitted is a constant proportion of the object contrast.

Campbell & Green (1965) have shown that sensitivity is also affected by neural factors which cause an additional blurring of information at high spatial frequencies. Part of the neural loss is due to the finite size of the retinal mosaic. This influence will also act linearly and transmit to the brain a constant proportion of the retinal image contrast. Additional loss of contrast may be due to the convergence of retinal receptors on to ganglion cells. In this case there seems to be little evidence one way or the other for linearity, although the success of linear approximations to the visual response (Enroth-Cugell & Robson, 1966; Kulikowski & King-Smith, 1973) makes it reasonable to assume that this too acts linearly. Thus a large part of the loss of contrast sensitivity at high frequencies is due to linear processes attenuating the visual signal, and possibly the loss is entirely linear.

If apparent contrast were encoded by the amplitude of the afferent signal then the loss of sensitivity at high frequencies would be accompanied by a proportional loss of apparent contrast above threshold. In Text-figs. 1 and 2 this would be represented by a series of parallel equal-contrast curves having the same shape as the threshold function. The results show that this is not the case. Indeed, above threshold, apparent contrast agrees with the physical contrast in the object, and whatever determines the sensitivity at threshold does not affect apparent contrast. The visual system must therefore restore the blurred signal by some kind of active compensation process. We call this phenomenon 'contrast constancy', by analogy with other constancies in vision.

The problem of compensating for losses due to imperfect transmission of information is one which arises in many branches of engineering. Probably the most familiar example is that of the frequency compensating networks used extensively in audio equipment, where the transducers typically have biased (temporal) frequency responses. Equalization circuits and tone controls are introduced in the amplifiers to produce a flat response over-all.

A less familiar example has a more immediate parallel with the visual system, and in this case compensation is effected explicitly in the Fourier transform domain. The image formed by any optical system is affected by aberrations inherent in the optics, and in some applications it is not possible to improve the optics to give the required resolution. Fourier methods have been applied with great success to improve effective image quality, e.g. the remarkable improvements seen in computer-processed space photographs (Nathan, 1968), and in the increased detail seen in electron micrographs (Stroke, 1971). In neither case is the *resolution* improved, since the information must be available in the original, but the fidelity of reproduction within the resolution limit leads to a vast improvement in image quality.

To illustrate the technique, a demonstration is reproduced from Gennery (1973). On the left of Pl. *1A* is an unrecognizable picture taken through an imperfect optical system. The Fourier transform of the picture contained a circular pattern of zeros, characteristic of a defocused circular lens. Deducing that the blur is due to defocus enables one to estimate the m.t. function of the imaging system. It is then possible to correct the picture by multiplying its Fourier transform by a function which is the inverse of the m.t. function. The resultant spectrum is resynthesized and gives the output shown on the right in Pl. *1A*. Information that was apparently unavailable in the original has been recovered, and this is accomplished with no information other than that in the original image (apart from theoretical knowledge of the effects of optical aberrations).

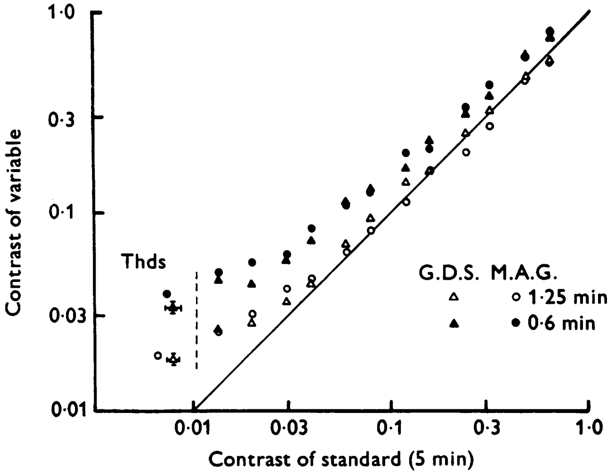
We suggest that the visual system employs a similar method to compensate and correct for the optical and neural blurring discussed earlier. There is overwhelming evidence that the visual stimulus is analysed by channels that respond selectively to different bands of spatial frequency, so that the separate Fourier components are, to a first approximation, independently processed. If, in each channel, there were a stage whose gain was the inverse of the gain of the preceding stages, then the over-all gain of the system would be constant for all spatial frequencies. Thus a system of spatial frequency channels could very easily achieve a flat frequency response to give the desired compensation for blurring. Note, however, that the contrast sensitivity function would be independent of this compensating stage. A change of gain would not affect the signal/noise ratio, and thus would not affect the threshold.

2. *The apparent contrast of single lines*

The threshold of a single line seen foveally is almost independent of the width of a line for widths greater than about 5 min. With narrower lines there is a gradual increase in threshold and for widths less than about 1 min threshold intensity trades off against line width so that the stimulus energy is constant (Ricco's Law). The same technique as in the previous experiment was used to compare the apparent contrasts of lines whose thresholds were different. The question of interest was whether or not the spatial summation (and consequent blurring) implied by Ricco's Law would be corrected above threshold.

Bright lines on a homogeneous background were generated on an oscilloscope by brightening individual rasters of the display. This technique avoids any instability at the edges of the lines. The raster density was 95/cm, i.e. 380/deg at the viewing distance of 228 cm. The oscilloscope suffered some blur due to the width of the spot and irradiation of the phosphor; this was measured by photographing a series of lines of different widths and contrasts. The negatives were scanned with a microphotodensitometer and the height and width of the traces were measured. The results showed that for lines greater than 4 rasters wide and for contrasts up to 60 % the display was reasonably accurate.

Two vertical lines each 1·75 deg long were positioned 0·5 deg apart in the centre of a single oscilloscope, which was masked off by an annular surround field whose internal and external diameters were 2 deg and 7 deg. The observer controlled the contrast of one of the lines (the variable) and set it to match the other (the standard) which was controlled by the experimenter. The task proved to be very easy since the observer was able to compare the apparent intensities of the lines directly, and with few exceptions (where the initial variability was high) only two matches of each pattern were made by each observer. Thresholds for the lines were also measured in the course of the experiment, and these were determined by at least six settings. In separate sessions the variable line was either 0·6 or 1·25 min wide (four or eight rasters); the standard bar was always 5 min (thirty-two rasters).



Text-fig. 3. Apparent contrast of single lines. Contrast of narrow lines which match a standard line in perceived contrast. Thresholds for the variable and standard lines are indicated in two dimensions by the left-most points, together with bars indicating ± 1 s.e. The diagonal line represents physical equality of contrast.

The results are shown in Text-fig. 3 where the contrast of the variable is plotted against the contrast of the standard. Thresholds for each pair of stimuli are shown by the symbols near the ordinate. Each symbol represents thresholds for both the standard and variable lines by its displacement along the abscissa and ordinate respectively. A line of slope + 1 through a threshold symbol would represent a difference between the contrasts of the two stimuli proportional to the difference in their thresholds. The diagonal in the Figure represents points of equality of physical contrast. The data show that matches of apparent contrast gradually conform to a physical match as the contrast of the standard increases.

There was a small shift in the settings with the 0·6 min line, and both observers consistently underestimated the brightness of this line. However, the effect was much smaller than the shift in threshold, and was probably due to imperfections of the display. The photodensitometric tracings showed that although the peak value was correct, there was no flat plateau of luminance with this very thin stimulus.

The appearance of a line and a grating were compared directly by matching the brightness of a 5 min line (variable) to the peak brightness of a 5 c/deg grating (standard). The results (for observer M.A.G.) again conformed closely to a match of physical intensities.

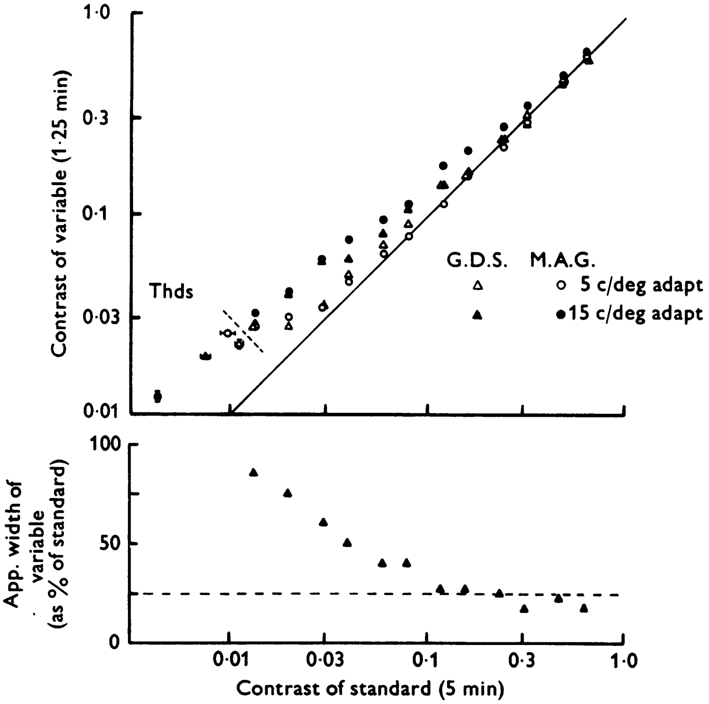
These results show that single lines are perceived correctly if the contrast is sufficiently high, and that the blurring implied by the differences in thresholds for lines of different widths is not maintained at high contrast. We interpret the findings in the following way. At low contrasts all narrow bars are detected by the channel which is maximally sensitive, that having a preferred frequency of about 5 c/deg. Differences in the thresholds for different lines are due in part to optical blurring but mainly to spatial summation of the stimulus within the receptive field of this channel. At high contrast other channels are also stimulated and the pattern of excitation in the system of channels reflects the Fourier spectrum of the line. The total response is corrected for variations in the sensitivity of the channels as described earlier. Thus the stimulus is encoded in the nervous system by an increasingly good approximation to its Fourier transform as more and more channels exceed threshold. Correspondingly, the fidelity of the percept gradually improves.

This explanation is in many ways very similar to that put forward by Kulikowski & King-Smith (1973). These authors also postulated a multi-channel system, but referred to the channels as different types of line detector. The most sensitive of these (the 'threshold line detector') correctly predicts the thresholds for narrow lines. At higher contrasts other, less sensitive mechanisms ('fine line detectors') also respond and by *inhibition* of the threshold line detector they dominate the response and correctly signal the width of the line. Suprathreshold apparent contrast was not considered, but to account for our results the various detectors would still have to be corrected for their differential sensitivity. Without suitable correction, a wide line (encoded by the threshold line detector) and a narrow line (encoded by the insensitive fine line detector) would show an error in apparent contrast even greater than that predicted by the two thresholds.

In our interpretation we have preferred to characterize the different channels by their tuning properties rather than their spatial response, because of the parallel with the Fourier deblurring techniques. Both apparent width and contrast can be accounted for by supposing that the percept is encoded by the *total* response of the system of channels, which approximates the Fourier transform more accurately at high contrasts.

The apparent contrast of lines after adaptation to gratings

In a previous study (Sullivan *et al.* 1972), it was found that thresholds for lines of all widths were raised after adaptation to sinusoidal gratings of 5·5 c/deg, but were unaffected by adaptation to 16 c/deg. This result may be understood in terms of either of the multi-channel hypotheses, since the most sensitive channel (or the threshold line detector) responds well to 5·5 c/deg but hardly at all at 16 c/deg. We have now investigated the effects of the two different adaptation conditions on the suprathreshold appearance of lines. The experimental method was the same as above except that between trials the display was filled with an adapting grating which in separate sessions was either 5 or 15 c/deg. The variable line was 1·25 min wide and the standard was 5 min wide.



Text-fig. 4. Appearance of single lines after adaptation to sinusoidal gratings. Top: apparent contrast of lines, as Text-fig. 3, after adaptation to gratings of 5 and 15 c/deg. Bottom: apparent width of 1·25 min line, compared to 5 min standard, after adaptation to 15 c/deg. The lines were matched in apparent contrast. The correct ratio of widths is given by the broken horizontal line.

The results of the contrast matches are shown in Text-fig. 4 and the threshold elevations obtained are given in Table 1. As in the previous study adaptation to a 5 c/deg sinusoidal grating raised the thresholds of both bars. However, the contrast matching result for bars was unaffected, and the data are essentially the same as those in Text-fig. 3 for the unadapted eye. Adapting to 15 c/deg gave very different results. Thresholds were hardly affected but the accuracy of the contrast matches was severely disrupted. At low to medium contrasts both observers consistently set the thin line to too high a contrast (i.e. thin lines looked dimmer) and the loss of apparent contrast approximately equalled the threshold difference between the lines. The effect progressively disappeared and at high contrasts correct settings were made once again. Both observers noticed a striking change in the appearance of the lines after adaptation to the 15 c/deg grating; the edges of both lines appeared blurred, and the thin line seemed very much wider than it had previously appeared. Neither effect was present after adaptation to 5 c/deg. For one observer (G.D.S.) the apparent width of the thin line was estimated (as a fraction of the standard line) when their contrasts appeared equal. These results are also shown in Text-fig. 4. At low contrasts the two lines looked almost identical, but at higher contrast the width of the thin line was seen correctly. The contrast at which the line was seen correctly in width corresponds to that needed for correct apparent contrast.

TABLE 1. Threshold elevation in log units

	Adapting frequency		
Test stimulus	5 c/deg	15 c/deg	Observer
Grating	0·504	0·792	M.A.G.
(= adapting frequency)	0·448	0·709	G.D.S.
Line	0·358	0·006	M.A.G.
(5 min)	0·316	0·146	G.D.S.
Line	0·351	0·033	M.A.G.
(1·25 min)	0·237	0·174	G.D.S.

These results can be understood if we consider the Fourier spectra of the two lines. The 5 min line has its energy concentrated in the low frequency region, with its first zero at 12 c/deg. The 1·25 min line has a more extended spectrum with its first zero at 48 c/deg, but relatively less energy at the low frequencies. Adaptation to 15 c/deg produced a loss of sensitivity to the high spatial frequency content of the narrow line. The response of the visual system would then be akin to that produced by a wider line of lower contrast, which is just what was seen. The effects of adaptation diminished at high test contrasts, as was also found for gratings (Blakemore *et al.*

1973). On the other hand, adaptation to 5 c/deg has little effect at high frequencies and both lines appeared sharp. Its effects are confined to medium frequencies which influence both spectra in the same way. Hence there was no change in contrast matching in this condition, even though the thresholds for both lines were raised.

These experiments with single lines illustrate an important aspect of our hypothesis: by adjustment of the gain functions of frequency selective channels, the visual system is able to correct automatically for the blurring of any input pattern (within the limits imposed by the selectivity and thresholds of the channels).

3. *Apparent contrast of band-pass filtered pictures*

We have suggested that the equalization of the visual system's spatial frequency response provides a general mechanism applicable to any stimulus. It may be argued that in the case of both gratings and single lines the stimulus is so simple and so familiar to the observer that contrast is set accurately by *ad hoc* knowledge of the significance of the blurred image. One reply is that our main findings have been confirmed using naive observers, but nonetheless we would like to justify our arguments by experiments using less redundant stimuli. One situation in normal vision where contrast constancy may be of demonstrable value to the observer is in comparing objects at different viewing distances. The c.s. function is dependent on angular spatial frequency, so that the same object viewed from different distances is affected in different ways. The c.s. function of the visual system acts as a band pass filter at least 7 octaves wide (cf. the 100-fold range of frequencies in Text-figs. 1 and 2). Over the limited range of viewing distances an observer might use to inspect any particular object – say 6 in. to 6 ft. for a photograph – there is a large overlap in the band of frequencies passed.

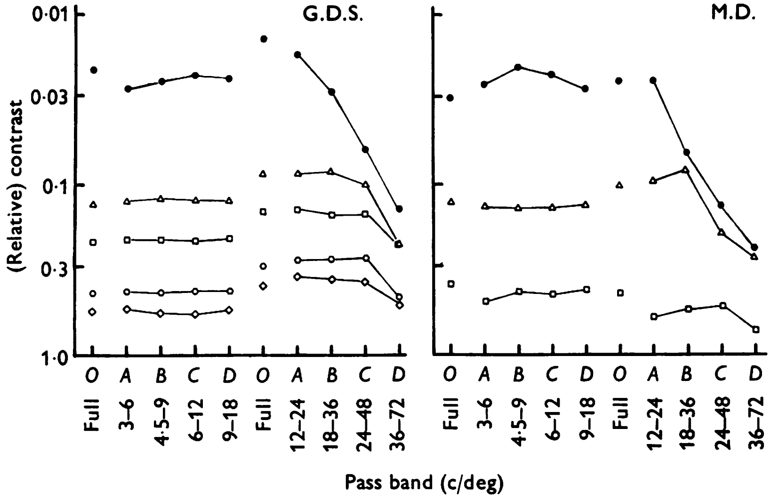
The effect of different viewing distances can be made more pronounced by using objects which themselves contain only a narrow band of frequencies thereby ensuring that there is no overlap in the visual response at reasonable viewing distances. For example, patterns one octave wide, viewed at distances differing by a factor of 4, give rise to retinal images whose frequency components are separated by a gap of one octave. The response in the channel system to such patterns will be very largely distinct. Under these conditions how similar do the two patterns appear? In the following experiment observers adjusted the contrast of one such pattern to match that of the other.

The patterns used were photographic slides of a chess board which were produced by spatial frequency filtering of the original in coherent light. The techniques used will be reported elsewhere (G. D. Sullivan, in preparation) but briefly the process involves generating a diffraction pattern of the original which represents its Fourier transform, and then retransforming the diffraction pattern to synthesize the original. The transform may be filtered through a mask to block all but a desired range of frequencies, and then the final image combines only these frequency components of the original spectrum. It is necessary to pass the d.c. component (the mean luminance level) and a small range of very low frequencies around it. The stimuli used consisted of this low frequency lobe plus a one octave wide band of higher frequencies which was at least 4 octaves away. Four such pictures were used with successively higher pass bands. An example of the stimuli is given in Pl. 1 *B*; this is the pattern labelled *C* in the results shown in Text-fig. 5. While this pattern is not exactly 'normal', it is recognizable as a chess board and is a far more complicated stimulus than the lines and gratings used previously.

The contrast of the patterns was controlled by combining the projected image of the pattern with the image of the d.c. component alone through a system of crossed polarizing screens. In this way any desired attenuation of the contrast could be achieved without affecting the mean luminance of the stimulus, and without affecting imperfections of the filtered picture due to unintended diffraction effects in the filtering process. Only the contrast of the pass band was varied.

The observer inspected two screens containing *identical patterns*. One (the standard) was always viewed at a distance of 1 m where it subtended 10 × 6 deg; the variable was viewed at either 1 or 4 m. The observer's task was to adjust the contrast of the variable until the two displays seemed identical; in addition he made contrast threshold settings for each pattern. Neither of these tasks was easy. As the contrast was increased some parts of the pattern were seen before others, because the local contrast in the stimulus varied. Threshold was taken as the contrast at which the most prominent part of the pattern could be seen. When the viewing distances of the two screens were equal, contrast matches were fairly simple because the stimuli corresponded exactly, but with unequal viewing distances the judgement depended on which part of the pattern was inspected. Observers were instructed to pay attention to the part of the pattern that they had used in setting the thresholds; this in fact accorded with the observer's own judgement of the optimal match.

Four band-passed pictures were used which contained frequencies of 3–6, 4·5–9, 6–12, and 9–18 c/deg at the viewing distance of the standard. At 4 m the pass bands were shifted up by 2 octaves. In addition to these a picture corresponding to a full pass through the optical filtering system was also used. The results are shown in Text-fig. 5, for two observers, one of whom (M.D.) was unaware of the purpose of the experiment. For each of the observers the results are in two parts. The left-hand part shows the results obtained with the same viewing distance for both the standard and variable. The data shown by filled circles are the threshold values for each of the five patterns. The ordinate shows the amount by which the contrast of each picture was attenuated, and therefore the results are not directly comparable between different pictures. However, it may be seen that neither observer showed any marked difference of sensitivity to the different patterns. The other symbols in the Figure show the result of the contrast matches. The standard had a constant (relative) contrast for each set of data shown by a particular symbol. The matches at each standard contrast are about the same, as is expected. This merely shows that observers were able to make consistent and reliable settings for the equal viewing distance condition.



Text-fig. 5. Apparent contrast of band-pass filtered pictures. Five pairs of pictures (*O*, *A–D*) were produced by filtering a single original, and each pair contained a different band of spatial frequencies; *C* is reproduced in Pl. 1 *B*. One member of each pair was used as the standard and the other as the variable; thus in any one trial the two pictures were the same. The standard was viewed from 1 m and the variable was viewed either from 1 m (on the left of the Figure, for each observer), or from 4 m (right). Different open symbols refer to different attenuations of the contrast of the standard; the data show the contrast of the variable which the observer matched to that of the standard, under the two viewing conditions. The filled circles give the contrast thresholds for the pictures. All contrasts are expressed relative to the contrast of the unattenuated pictures.

The right-hand side of the results for each observer shows the equivalent results obtained when the viewing distances were different. Both observers show a strong loss of sensitivity at higher pass bands, as is to be expected from the c.s. function of the visual system, but contrast matches are hardly affected. Two comparisons can be made. Matches for the different stimuli at the same (relative) contrast are more or less flat, just as they are when the viewing distances are equal. They do not show the very strong change exhibited by the threshold settings (except where the threshold function traps the matches, particularly M.D. triangles). Secondly, the contrast of any particular stimulus which matches a given standard contrast is similar whatever the viewing distance, even though sensitivity is very different. (The results for G.D.S. show that the more distant stimulus actually needs less contrast to match the near one. This is probably artifactual, and may be due to differences of background lighting at the two viewing distances.)

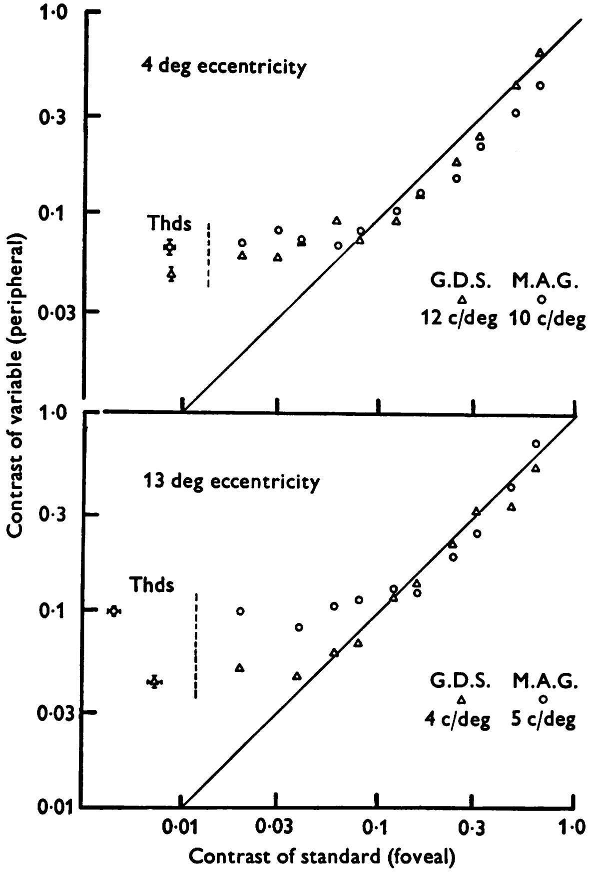
This experiment was too poorly controlled to allow for fine interpretation of the results. The method of adjusting the contrast of the stimuli was insensitive and in the only room long enough to set up the apparatus the viewing conditions were far from ideal. There is also great uncertainty associated with the ambiguity of the threshold. Nonetheless the results show that the loss of sensitivity at threshold in the distant viewing condition is not present in contrast matching results. This confirms that the effects reported in the previous experiments are not merely due to *ad hoc* knowledge of the simple stimuli, but represent the operation of an active compensation process applicable to any stimulus.

So far in this paper we have considered compensation for losses of sensitivity due to optical and neural blurring in normal foveal viewing, and have mainly been concerned to demonstrate the generality of the process for a variety of stimulus patterns. The next three experiments studied a variety of viewing conditions to determine whether compensation also occurs for changes in sensitivity due to anisotropies in the visual system and variations of viewing conditions.

4. *Apparent contrast in peripheral vision*

The sensitivity of the eye to sinusoidal gratings is much reduced if the pattern is viewed outside the fovea, and the difference in sensitivity increases with spatial frequency (Daitch & Green, 1969; Hilz & Cavonius, 1974). This finding correlates well with neurophysiological findings that both retinal and cortical receptive fields are larger in the periphery (Enroth-Cugell & Robson, 1966; Hubel & Wiesel, 1965). In the following experiment the apparent contrast of a sinusoidal grating seen in peripheral vision was measured by matching it to a grating of the same frequency viewed foveally. The apparatus and method were essentially the same as before. The subject fixated a small dot at the centre of the left-hand screen which showed the standard grating. The display was seen monocularly, using the left eye to avoid the blind spot. Two eccentricities were used: the centre to centre separation being either 4 deg (using a viewing distance of 228 cm at which the screens subtended 2 deg) or 13 deg (viewed from 114 cm, so that the displays subtended 4 deg). The spatial frequencies of the gratings were chosen so that there was a marked difference between the foveal and peripheral thresholds.

The results are shown in Text-fig. 6. At the frequencies chosen (see Text-fig. 6) the differences between foveal and peripheral thresholds ranged from 0·7 to 1·3 log units. Once the foveal grating exceeded the peripheral threshold, however, this difference was not maintained in the contrast-matching results, and observers made settings that were much closer to the physical match. In fact there seemed to be a slight tendency for observers to adjust the peripheral grating to too *low* a contrast, and this tendency was also shown by a naive observer. This could have been due to response bias or perhaps to the difficulty of the task. Perceptual fading of a peripheral target occurs very rapidly (the Troxler effect), and



Text-fig. 6. Apparent contrast in peripheral vision. Contrast of a sinusoidal grating (the variable) seen in peripheral vision which matched a grating of the same frequency seen foveally. Other conventions as in Text-fig. 3.

it is very difficult to attend to details of the peripheral stimulus. These two factors forced the observers to adopt a less critical attitude to their judgements, and may well have introduced bias into the results. Whether or not this 'overshoot' is genuine, it is very clear that the differences at threshold are not present above threshold. Once again observers reported the paradox that the peripheral grating might be barely visible yet have much greater apparent contrast than the easily visible foveal grating.

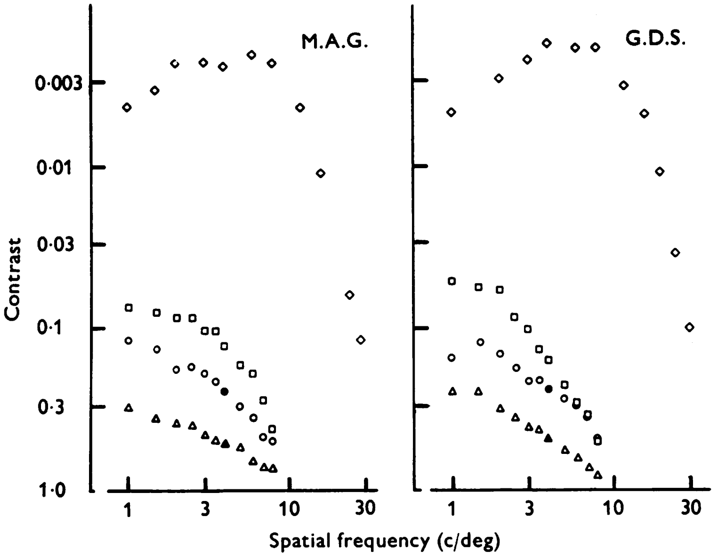
These results show that a grating is seen to be of the same contrast whether it is viewed foveally or peripherally, provided it is seen at all. Increased spatial summation in the periphery has a very strong effect on the threshold, but does not affect suprathreshold vision. The contrast constancy hypothesis accounts for this simply by assuming that the gain functions of peripheral channels (Sharpe & Tolhurst, 1973) are adjusted to compensate for the neural blur at each particular retinal locus. The effect of such an organization is to make the perceived image partially independent of its position on the retina. The correction is of course far from complete, because information is irretrievably lost if the excitation of a channel is below threshold, and this accounts for the loss of fine detail in peripheral vision. A simple demonstration may point to the distinction between loss of detail and loss of contrast. The reader should fixate a page of evenly spaced print, and compare the visual impression of the contrast between the black print and the white page at different eccentricities. Individual letters are legible only around the fixated point, and further into the periphery all detail is progressively lost. However, there is very little concomitant loss of contrast; the ink does not appear to fade to light grey away from the fovea. More generally, the visual impression of a fixated scene is not that of looking through a fog which gets progressively thicker in peripheral vision; objects look as bright and contrasting, but fine detail is lost.

5. *Apparent contrast in scotopic conditions*

At scotopic levels of illumination the contrast threshold for gratings is greatly increased for all spatial frequencies (Campbell & Green, 1965; De Valois, Morgan & Snodderly, 1974). It seems likely that this is due to functional reorganization at the retina, leading to an increased convergence of receptor responses on to ganglion cells. Barlow, Fitzhugh & Kuffler (1957) found that the inhibitory surround of cat ganglion cells disappeared at low levels of illumination, and Arden & Weale (1954) have shown psychophysically that there is greater spatial summation. In the next experiment contrast matching was studied in scotopic conditions to see if the losses of sensitivity at threshold were also present in suprathreshold apparent contrast.

Contrast matches were made between a standard grating of 4 c/deg and a variable grating covering a range of spatial frequencies, essentially as in the first experiment. The observer initially made photopic threshold settings to establish a base line. He then wore binocular goggles of 3·3 log units neural density filters, and sat in a darkened room for about 90 min, to dark adapt the eyes. The scotopic sensitivity function was measured and two sets of equal-contrast curves were plotted out. The viewing distance was 114 cm.

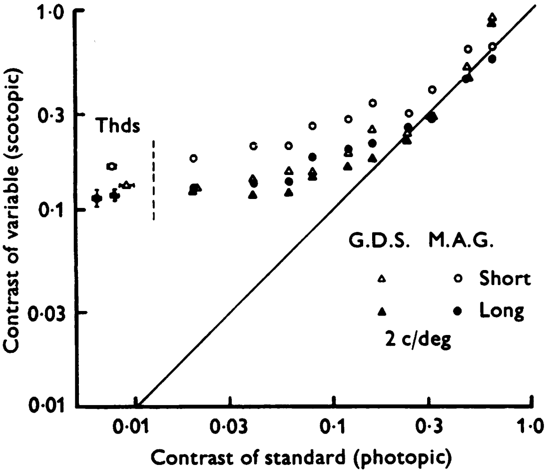
The results are shown in Text-fig. 7. The effect of dark adaptation on sensitivity is very marked, causing an over-all loss of sensitivity of up to 2 log units. But again the effect on suprathreshold matches was less at the higher frequencies. The region between 3 and 8 c/deg is of particular interest: in photopic conditions there is very little change of sensitivity in this region, whereas sensitivity falls off by about 0·7 log units in the dark. In photopic viewing the equal-contrast contours are flat and are approximately parallel to the threshold function over these frequencies (see Text-fig. 1). However, in scotopic viewing thresholds are affected more by changes of frequency than are the contrast matches and the functions converge. This suggests that there has been a dynamic reorganization in the visual system which changes the suprathreshold response to compensate, at least in part, for the changes in threshold sensitivity at different frequencies. Unfortunately, the region of frequencies which allow this com-



Text-fig. 7. Apparent contrast in scotopic conditions. Diamonds: photopic c.s. function. Squares: scotopic c.s. function. Circles and triangles: contrast matches in scotopic conditions between (variable) gratings of different frequencies and (standard) gratings indicated by the filled symbols.

parison and the range of suprathreshold contrasts available in scotopic conditions is too small for this interpretation to be very conclusive but we take the evidence of Text-fig. 7 as indicating that the visual system can change its response to compensate for changes in threshold due to dark adaptation.

In a second experiment we compared apparent contrast in scotopic and photopic illuminations by dark adapting one eye only and matching a grating seen in the dark adapted eye to one of the same frequency presented to the other eye. The experiment was carried out in two ways: (1) the observer wore a monocular goggle containing a neural density filter of 3·8 log units and he fully adapted to the reduced illumination for about one hour before the experiment; (2) in a second condition he kept both eyes at the same photopic adaptation level but applied the goggle only seconds before making the judgement. The results were essentially the same, which indicates that the brighter adapting luminance was not sufficient to cause any significant photopigment bleaching and that the dark adaptation processes were principally neural with short time courses. The luminance of the screens was about 10 cd/m^2 (giving retinal illumination of about 200 trolands) and published data on thresholds during dark adaptation support this interpretation (Hecht, Haig & Wald, 1935; Dowling, 1967).



Text-fig. 8. Apparent contrast in scotopic conditions. Contrast of a sinusoidal grating seen by one eye in scotopic conditions which matched that of a similar grating seen photopically in the other eye. The two conditions show matches made immediately after applying the N.D. filter to the scotopic eye (open symbols), and after dark adapting for 1 hr (filled symbols). Other conventions as in Text-fig. 3.

Phenomenally, the task was difficult since the dark condition was well below the levels over which brightness constancy holds and the screens looked very different in the two eyes. The light adapted eye saw a bright screen, strongly coloured green; in the dark eye it appeared as a dim, uncoloured screen whose details were very difficult to make out. The bright bars of the dark screen appeared much darker than any part of the light screen. In this case it was impossible to do the task on a basis of matching the brightnesses of the light and dark bars of the different screens and observers were forced to make settings according to the internal contrast of each screen.

The results of both conditions are shown on Text-fig. 8. It is immediately apparent that at high contrast levels the observers made matches which closely approximated the true, physical match, even though the thresholds in the two eyes were different by more than a log unit. Once again the suprathreshold appearance of a grating is independent of factors which affect its threshold.

It might be argued that these two experiments are merely a strong demonstration of the classical idea of brightness constancy (see Hochberg, 1972, for a recent review), which may be explained by lateral inhibition (Cornsweet, 1970). However, lateral inhibition will explain the results of the first scotopic experiment only if the shape of the inhibitory function remains the same in the two viewing conditions, and will explain the results of the second experiment, only if the contrast response of the function remains the same. In either case, other factors must be introduced to explain changes in the thresholds. Physiological evidence shows that neither assumption is true for the retinal ganglion cells of cats (Barlow *et al.* 1957; Enroth-Cugell & Robson, 1966). In any case, the apparent brightnesses of the two screens in our second experiment were very different, and this effectively rules out a brightness constancy explanation.

6. *Vision in astigmats*

Mitchell, Freeman, Millodot & Haegerstrom (1973) found that astigmats had a residual loss of acuity and contrast sensitivity for gratings oriented along the poor meridia even when the observers were optically corrected. They suggested that the defect was of a neural origin, resulting from a lack of early visual experience of sharp contours in the blurred orientations. Investigations of the effects of early visual experience on the physiological organization of the cortex of cats (Hirsch & Spinelli, 1971; Blakemore & Cooper, 1970) have shown that a lack of experience of lines of a particular orientation at a critical phase of development leads to more or less permanent lack of cells tuned to that orientation. In the following experiments contrast-matching was tested in astigmatic subjects, in order once again to see if the attenuation at threshold was reflected in suprathreshold apparent contrast.

The apparatus was essentially as before, except that one of the oscilloscopes was mounted on a rotating frame so that gratings could be presented at any orientation. The screens subtended 4 deg at a viewing distance of 114 cm.

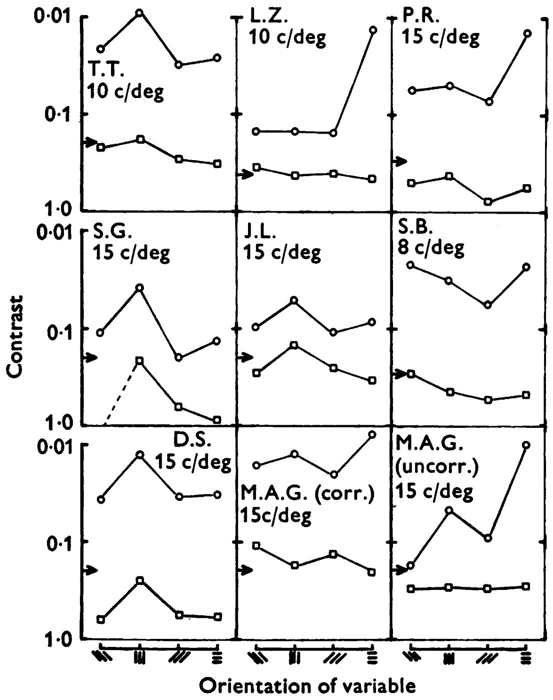
The astigmatic observers (mainly students) were all normally corrected, and used their ophthalmologically prescribed lenses during the experiment. One (L.Z.) wore contact lenses. Viewing was monocular; some subjects had marked astigmatism in one eye only and this was the eye used in the experiment; others had binocular astigmatism in which case they were free to use their preferred eye.

For each observer a spatial frequency was chosen such that the contrast threshold was about 10%. One could thus hope to find a large meridional amblyopia whilst having a sufficient range of contrasts to make satisfactory contrast matches. Thresholds were measured at each of four orientations: horizontal, vertical and the two 45 deg obliques. Depending on the observer's consistency four to six settings were made for each threshold. In the next phase of the experiment a standard vertical grating was presented on the left-hand screen and observers were asked to set the contrast of the rotatable grating to look the same as the vertical one. It was stressed that the judgement should be one of contrast, i.e. the relative brightnesses of the bright and dark bars within each grating.

In all, thirteen astigmatic observers were tested. The results for two subjects have been excluded since their thresholds varied very little with orientation. The data from a representative group of seven observers are shown in Text-fig. 9 (for discussion of M.A.G. see below). Open circles show the contrast sensitivity and squares show the contrast matches made to the standard (vertical) grating whose contrast is indicated by the arrow. In agreement with Mitchell *et al.* (1973) most of the observers showed a residual difference of sensitivity even though they were optically corrected.

Some of the observers made contrast matches which closely followed the threshold functions, most notably D.S. and J.L. (Text-fig. 9) and for these subjects there was little evidence of suprathreshold compensation for the loss of sensitivity at threshold. Other observers showed varying degrees of improvement in the matching task over the threshold amblyopia. A startlingly clear example of this was L.Z.; notwithstanding an enormous loss of sensitivity for all but horizontal gratings, this observer made contrast matches that were extremely accurate, and therefore suprathreshold gratings of all orientations appeared equal in contrast. No other results were quite so impressive but for most of the observers the contrast matching functions were considerably flatter than the threshold functions, indicating at least partial correction.

To assess the over-all result we devised a single measure of the extent of correction shown by each observer. For each observer the results were replotted with the contrast match on the ordinate against the threshold contrast on the abscissa for each of the four orientations. If there were no compensation, then the shape of the two original functions would be the same; on the new plot the points would be perfectly correlated and should lie on a straight line of slope +1. On the other hand if full compensation occurs then the contrast matches are constant, independent of threshold, and the points should lie on a line of slope zero. The measure of compensation was $(1-m) \times 100$ where m is the slope of the regression line fitted to the new plot.



Text-fig. 9. Apparent contrast in optically corrected astigmatic observers. Each panel shows contrast thresholds for sinusoidal gratings of four orientations (circles) and the contrast of the variable (squares) which matched that of a vertical standard whose contrast is indicated by the arrows.

Table 2 shows the compensation scores obtained for each observer. Before calculating the compensation scores we had classified the observers as showing high or low compensation, by inspection of the raw data. The suitability of the compensation score is attested by the fact that all those classified as 'high' compensators showed scores greater than 55 % (mean 88 %), whereas those classified as 'low' scored less than 35 % (mean 18 %). The over-all mean score was 56·2 % and was significantly greater than zero ($t = 4{\cdot}39$, d.f. $= 10$, $P < 0{\cdot}005$). There was no significant correlation between the compensation scores and the amount of meridional variation in threshold.

In Text-fig. 9 the bottom two panels in the right-hand corner refer to one of the authors (M.A.G.). This observer has one eye which is approximately 1·25 D astigmatic (simple hypermetrope) but he wears no correcting lenses. We wondered what would be the effects of this long term experience of optical blurring on contrast matching ability. Would he show correction of apparent contrast suitable for his usual astigmatic condition? What would be the effect of correcting the defect?

TABLE 2. Compensation scores for astigmats

High					Low			
Subject	Sp. freq. (c/deg)	Contrast of Std.	Score (%)		Subject	Sp. freq. (c/deg)	Contrast of Std.	Score (%)
M.A.G.	15	0·10	110	135				
M.A.G.	15	0·20	161					
L.Z.	10	0·50	106·5		D.C.	15	0·20	32·7
P.R.	15	0·30	93·3		S.G.	15	0·20	17·6
D.G.	15	0·30	76·1		J.L.	15	0·20	16·8
S.B.	8	0·30	59·4		D.S.	15	0·20	14·6
T.T.	10	0·20	55·7		D.J.G.	20	0·40	10·0
Mean (n = 6)			87·7		Mean (n = 5)			18·3

The right-hand panel at the bottom of Text-fig. 9 shows the results of the experiment with this observer without optical correction. He suffered a severe loss of sensitivity at all but his emmetropic meridian, but the contrast matches were perfectly flat. It may be objected that above threshold the eye was able to change its accommodation according to the orientation presented, but that this was not possible at threshold since there was insufficient detail to stimulate accommodation. However, astigmatic optics can only focus in the two principal meridia, and for this observer the retinal image of oblique gratings could *never* be sharp. Therefore although the threshold function might be exaggerated, correct matching of oblique gratings indicates the presence of contrast compensation.

The centre panel at the bottom of the Figure shows the results obtained for M.A.G. when he wore a corrective lens. In this case the meridional amblyopia is much reduced although a significant effect remains. The effect on the contrast matching function is interesting. Instead of being flat it now shows meridional variation which is the *opposite* of the threshold variation, giving scores greater than 100 % in Table 2. It seems that the compensation process suitable for his uncorrected eye overcompensated the abnormally sharp image obtained when a correcting lens was worn.

In summary, about half the astigmatic observers showed considerable compensation for their orientation specific deficit in contrast sensitivity. This deficit is almost certainly of cortical origin, unlike our previous experiments where the losses were largely attributable to optical or retinal factors. The reason why some observers exhibit compensation and some do not may involve the age at which they were given correcting lenses (Mitchell *et al.* 1973).

DISCUSSION

The appearance of gratings at threshold

A striking observation runs through many of the experiments in this report: at threshold, gratings whose threshold is high look very different from gratings whose threshold is low. When the contrast of a low threshold grating is slowly increased there is a continuous, gradual change in the percept. At threshold the brightnesses of adjacent bars are almost indistinguishable. High threshold gratings, on the other hand, seem to rise above threshold with a rapid, almost discontinuous change from a homogeneous screen to a pattern of high contrast. This effect can be noticed under a wide variety of conditions leading to high contrast thresholds: high spatial frequencies, scotopic viewing, peripheral viewing, and the neural deficit presumed to occur in astigmatism. The paradox that gratings which match each other in contrast may not be equally distinct has been spontaneously reported by naive observers in all of these conditions.

We suggest that the visual system corrects for contrast losses caused by blurring of the image early in the visual process. This would help to make the perceptual response to an object invariant, and independent of the viewing conditions. Drawing the analogy between this effect and the invariances observed in shape, size and brightness constancy, we have called the effect contrast constancy.

The mechanism of contrast constancy

A very convincing amount of evidence has been accumulating in the past few years that shows that the visual system contains a large number of more or less independent channels which process the incoming information in parallel. Some workers have described these channels in terms of their response to spatially simple stimuli, such as lines and edges (e.g. Hubel & Wiesel, 1962, 1965; Kulikowski & King-Smith, 1973); others have characterized them by their tuning properties to sinusoidal gratings (Campbell & Robson, 1968; Blakemore & Campbell, 1969; Maffei & Fiorentini, 1973). These descriptions are equivalent, for in either case the units respond only to a limited band of spatial frequencies.

The spatial distribution of an object must be encoded by the response in the system of channels; in a convenient language (which should not be taken too literally) one may think of the encoding as being in the Fourier domain. (Strictly speaking, the Fourier transform represents a spatial signal as a distribution of frequencies in which the topography is lost. A system of channels which have limited receptive fields cannot perform a genuine Fourier transform (since the tuning characteristic is of finite width), and in the visual system topographical information is preserved. A close analogy exists between such a process and the sound spectrogram, which represents a running spectrum of the signal, analysed over a short period of time, thereby preserving temporal information.) The encoded representation will be affected by anisotropies and by attenuation of high frequencies. If such losses are due to linear processes (and some certainly are, as discussed earlier) then attenuation of sensitivity at threshold should be accompanied by a proportional loss above threshold. This is not the case. Subsequent processes must therefore act to compensate for these losses.

One possibility is that the channels adjust their gain so as to flatten the over-all frequency response of the visual system. Suppose the blurring of a sinusoidal grating due to optical and neural processes attenuates the signal by a factor A, which determines the threshold. When the contrast of the grating is raised above threshold the detecting channel receives a reliable signal, and needs only to adjust its own gain by a factor equal to $1/A$ to correct for the effects of the blurring. To do this the channel needs to 'know' the attenuation, A. A simple means of achieving this is for the channel system to assume that the total stimulation received over a period of time has a flat spectrum. Any systematic bias in the relative responses of different channels would indicate attenuation by more peripheral processes. This information could be fed back to adjust the gains of the channels accordingly. The final result would not affect the threshold function (the c.s. function), but would correct the suprathreshold percept. In the example of Fourier deblurring given in Pl. 1A the blur function has to be inferred from the image spectrum. This procedure is susceptible to a potential artifact, since the information in the spectrum that is used to estimate the blur function may in fact be due to the object itself, and erroneous reprocessing will then produce a false final image. The visual system could base its correction on a continuous sampling of images over a considerable time interval and thereby avoid this pitfall. The self-regulating system proposed here is very speculative, but is attractive because it suggests a simple method of achieving contrast constancy, which requires no *a priori* knowledge of the blur itself. The compensation process is local and could be adjusted to suit the particular conditions at different retinal loci, and for changes in dioptric and retinal state.

The site of compensation

Our experiments have provided no direct evidence that the compensation mechanism is located in the visual cortex, or is a property of the system of channels. A re-analysis of Blakemore & Campbell's (1969) data has, however, provided strong indications that this is so. They noticed, but did not emphasize, that the slope of the function relating threshold elevation to adapting contrast seemed somewhat steeper at higher spatial frequencies. We fitted regression lines to their data (in each case $r = 0{\cdot}97$ or better) and then computed the correlation between the slope of adaptation and the unadapted contrast sensitivity for each spatial frequency. There was a highly significant linear relation between them ($r = -0{\cdot}96$, $P < 0{\cdot}005$, $n = 7$; $S = 2{\cdot}97 - 2{\cdot}83A$, where S = contrast sensitivity in log units, and A = the slope of log threshold elevation *vs.* log adapting contrast). The slope of adaptation increased from 0·27 at 10 c/deg to 0·47 at 20 c/deg, to over 0·7 at 28 c/deg. This implies that the gain of high frequency channels is boosted in direct proportion to the decrease in their contrast sensitivity.

Further support for this conclusion comes from Graham (1972), who found a similar increase in *adaptability* with spatial frequency (where adaptability was defined as log threshold elevation divided by log supra-threshold contrast of the adapting grating). The same trend can be seen in the data of Tolhurst (1972). In fact, Graham (1972) commented that the rate of increase of perceived contrast with real contrast (Watanabe *et al.* 1968) increased with spatial frequency in approximately the same way as adaptability and contrast threshold. She suggested that the underlying channels had steeper stimulus–response functions at higher spatial frequencies, but the reasons for this were 'not clear'.

We have proposed the mechanism of contrast constancy to account for the relationship between the gain of perceived contrast and contrast threshold. Since the gain of adaptation shows a similar relation to contrast threshold, it follows that at the site of adaptation in the visual cortex the signal has already been corrected. On the other hand, our experiment with astigmats indicates that the compensation mechanism can operate selectively on particular orientations. This rules out a pre-cortical locus, where orientation specificity is not present. The mechanism of contrast constancy must therefore lie *within* the system of cortical channels which are selective for both orientation and spatial frequency.

The increase in the gain of adaptation at high frequencies has a further interesting consequence. Blakemore & Campbell (1969) found that the spatial frequency tuning of adaptation was sharper at high spatial frequencies. The tuning curve of a channel, however, is best defined in terms of the 'equivalent contrast transformation' (Blakemore *et al.* 1973). This curve relates two sets of data: one expressing threshold elevation as a function of adapting contrast, the other expressing threshold elevation as a function of spatial frequency. The band-width of the channel should be given directly from the ratio between the slopes of the two sets of data. From Blakemore & Campbell's (1969) results we found that this ratio was nearly constant for all adapting frequencies. (The correlation between the two slopes was 0·90, with the intercept very close to zero. This was true for both the high and low frequency arms of the empirical tuning curves. The mean estimate of bandwidth was 0·22 octaves (half-width at half height) with an S.E. of 0·024.) This approximation to the equivalent contrast transformation strongly suggests that channels in the visual system actually have a constant band-width at all spatial frequencies.

The clarity of vision

The assumption that vision is not as limited by the image-forming process as might be expected has been made by many authors and several have previously considered processes which might achieve a deblurring of the retinal image. It has been argued that the shape of the c.s. function is due to a single lateral inhibition function (see Ratliff, 1965; Patel, 1966), and lateral inhibition is commonly thought to 'sharpen the image' (Hurvich & Jameson, 1966, p. 100) or 'rectify blurred contours' (Ratliff, 1965, p. 159). Campbell & Gubisch (1966) have pointed out that the results of Campbell & Green (1965) imply that any contribution made to image fidelity by the (single channel) lateral inhibitory process is confined to low frequencies that are hardly affected by optical blur. In the high frequency region where optical blur is severe, the image is further blurred by the nervous system. However, this argument against neural sharpening relies on threshold findings which, we have shown, do not predict suprathreshold performance.

Attempts to explain the appearance of Mach bands from the c.s. function have underpredicted the sharpness of the bands (Menzel, 1959; see Ratliff, 1965, p. 152). Lowry & De Palma (1961) inverted the logic of the calculation and used the subjective and objective distributions across a Mach band stimulus to estimate the transfer function of the visual system. Their results showed much better high frequency response than has been found with the threshold technique (see Ditchburn, 1973, pp. 270 and 289, for a direct comparison). The reason for this is evident in view of the contrast constancy hypothesis: high frequency channels which were adequately stimulated by the Mach stimulus have boosted their contribution to the perceptual response and do not show the attenuation present at threshold.

Direct evidence for better transfer of fine details at high contrasts than at threshold has been provided by Hay & Chesters (1972), who showed that the brightness of a small circular dot is perceived correctly even when threshold contrast approaches 100 %. Their experiments were rather similar to those of section 2, above. They commented: 'It is gratifying to realise that our suprathreshold vision appears to be some 10 times better than has been deduced from the threshold evidence.'

To explain their findings, Hay & Chesters (1972) suggested a single deblurring convolution (which must be rather like a laterali nhibitory process, but one which is much finer than that suggested by the c.s. function), together with an additional noise factor to account for the threshold evidence. One problem with this suggestion is that the deblurring process will also amplify the noise. This fact is illustrated by the optical deblurring technique of Stroke (1971), which is limited by noise present in the original photograph. Noise due to photographic grain, dust, or scratches, contain sharp details of the kind that the deblurring process will amplify in the final image (such noise can be seen in the deblurred picture of Pl. 1*A*). If the deblurring technique is used to give maximum reconstruction of the original, then the noise is also strongly amplified, and the final image is seriously degraded (see Stroke, 1972).

A single-channel deblurring process is therefore seriously limited by noise, but the multiple channel process suggested above would overcome the noise problem at source if each channel contributed to the percept only when its excitation level exceeded the channel's intrinsic noise level. By applying a threshold in the Fourier domain, only those frequencies which were due to reliable signals would be corrected. One could expect further improvement of Stroke's optical technique, if an equivalent method could be implemented optically.

This analysis suggests that the single channel process, though apparently simpler, would be inferior to deblurring performed by multiple channels acting in parallel. However, the main argument in favour of the multiple channel process in the visual system is that it is supported by physiological and psychophysical findings on information transmission in the visual system. Indeed, it points to a very powerful advantage due to this organization and helps to explain why it is that visual information is analysed by spatial frequency specific mechanisms at all.

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Note added in proof. Our attention has been drawn to an earlier use of the term 'Contrast Constancy' by Dr J. J. Kulikowski (meeting of the Experimental Psychology Society, Jan. 1972). Experiments with results similar to some of our own, but with a somewhat different analysis are to be published (Kulikowski, J. J. *Vision Res.* in the press).

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EXPLANATION OF PLATE

A, demonstration of deblurring by Fourier methods. On the left is the blurred original; on the right the improved picture produced by compensating for the transfer function of the original blurring process. For details see text (taken from Gennery, D. B. (1973), *J. opt. Soc. Am.* **63**, 1571–1577). *B*, one of the filtered pictures used in Expt. 3. It contains only a 1-octave band of spatial frequencies in all orientations.

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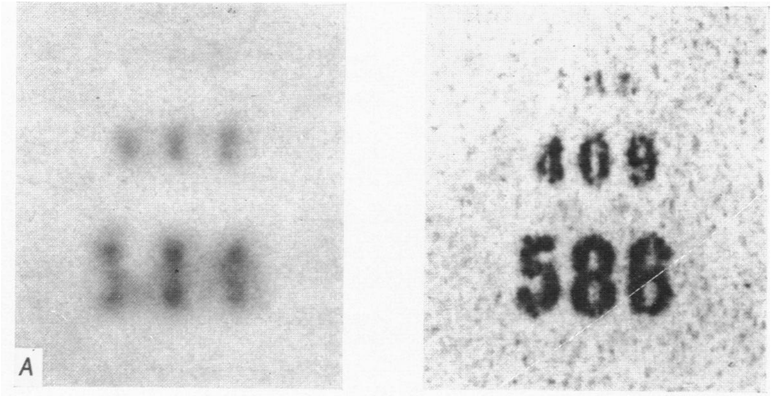

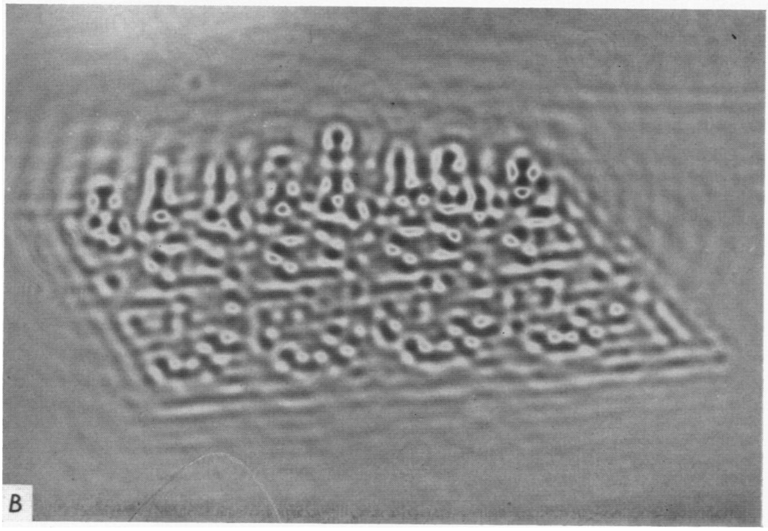

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