The importance of measuring contrast sensitivity in cases of visual disturbance

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SUMMARY   A description is given of a practical clinical test of contrast sensitivity and of the results obtained on a normal population. An account is given of recent physiological work which illustrates the potential usefulness of the method in ophthalmology, and the clinical results obtained by the author and others are summarised.

The ability to perceive sharp outlines of relatively small objects is of enormous practical importance. However, the ability to perceive slight changes in luminance between regions which are not separated by definite borders is of equal importance. In clinical practice it is only the first ability which is tested—by means of the Snellen chart, or some other optotype—and patients who complain of visual disturbance may have acuities of 6/6 or better. Usually such patients cannot describe precisely what the change in sensation is like. In the case of those with retrobulbar neuritis, for example, vision may be described as 'misty' or 'flat'. In one case the patient said 'it's as though the contrast was turned down on the television'. It is at present a nearly universal medical practice to ignore such reports. However, isolated losses of contrast sensitivity exist in certain diseases, and in many others loss of contrast sensitivity is more prominent and disturbing to the patient as the loss of visual acuity. The failure to assess or measure contrast sensitivity is a defect in our ability to diagnose disease and to monitor its progress. Physiological advances over the last 12 years have led to a good understanding of the nature of contrast sensitivity, and it has recently become possible to adapt laboratory techniques to clinical circumstances. The aim of this paper is to provide an introduction to this subject, which will provide a background for the clinical exploitation of physiological knowledge.

Some basic physiological investigations

Campbell and Green (1965) first measured the sensitivity of the eye to contrast, using sinusoidal

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grating patterns. The use of such targets was an important advance since it provided a simple means of specifying the performance of the eye over an entire working range. Figs. 1, *A, B,* and *C* show examples of sinusoidal gratings, together with their diagrammatic representation. It can be seen that such gratings can differ in only a few respects. One is the average amount of light reflected from the paper, which is determined by the illumination of the paper and the density of the ink. For all the gratings in Fig. 1 the average reflectance is constant, and since it can easily be controlled it is considered only briefly below (p. 202). The other two variables are the degree of blackness-to-whiteness, the *contrast,* and the distance between the repeats of the pattern (for a formal definition of contrast see the legend to Fig. 1). The contrast of the gratings in Figs. 1 *A* and *B* is nearly the same, but the contrast of 1 *B* is considerably higher than 1 *C*. The distance between repeats in 1 *B* and 1 *C* is the same, but in 1 *A* it is smaller—this is a 'finer' grating. The distance between repeats varies, in terms of the retinal image, as the observer moves towards or away from the page. It is therefore usually specified in terms of the visual angle, i.e., the number of grating periods, or *cycles per degree* of visual angle. The diagrams on the right of Fig. 1 show the output of an ideal reflection microdensitometer as it traversed the grating on the left in a horizontal direction. As the sensing head travelled over the white margin it would record a maximum, which would drop, and vary rhythmically as it traversed the grating. Such gratings are unfamiliar—they are never seen in nature—but a rough analogy shows why they are powerful investigatory tools.

Just as, in the field of hearing, any sound can be synthesised by combining a number of pure tones (sinusoidal sound waves) in the correct proportion,
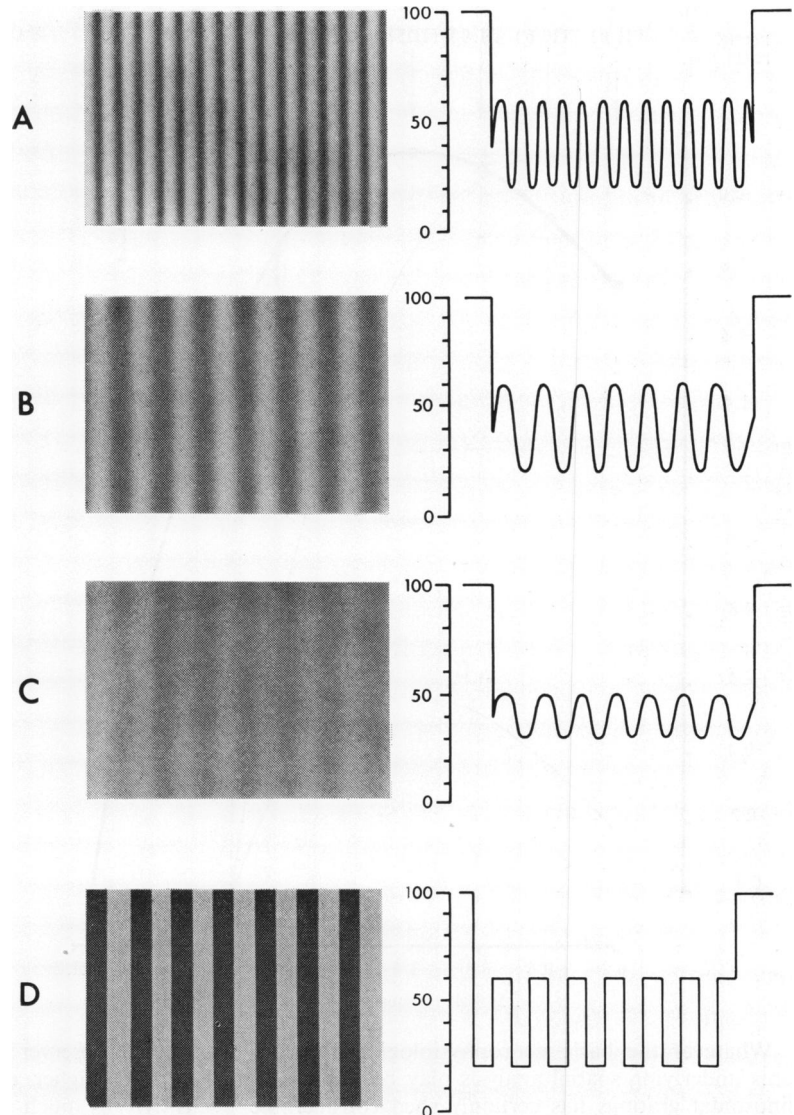
Fig. 1 *Examples of gratings. A, B, and C are sinusoidal, D square. A and B differ in spatial frequency, B and C in contrast. Contrast is defined as* $(L_{max} - L_{min})/(L_{max} + L_{min})$ *where L is the luminance recorded by a microdensitometer scanning across the gratings. This is diagrammed to the right of the Figure*

so, in theory, it is possible to construct any visual image by combining a number of sinusoidal patterns in space.

For example, Fig. 1 *D* shows a striped pattern of the same fundamental spatial frequency as 1 *C,* and of the same contrast, which is called, for obvious reasons, a 'square-wave grating'. Fig. 1 *D* can be synthesised from 1 *C* by adding *harmonics* (3rd, 5th, etc.) to the fundamental (Campbell and Maffei (1974) have an illustration). It is known that the ear acts as a frequency analyser and splits any complex sound into its harmonic components, which are transmitted separately to higher levels of the nervous system. It is still a matter of controversy whether a similar process occurs in the visual system (see Spekreijse and van der Tweel (1977) for summary). There is no obvious basis in retinal anatomy which would enable the eye to act as a spatial frequency analyser as there is in the structure of the cochlea. While pure auditory tones occur in nature, there are no natural visual equivalents. Nevertheless, it has been established that single cells in the visual cortex respond only to narrow bands of spatial frequencies and may respond more vigorously to a sinusoidal grating of optimal frequency than to a square wave grating or to any single line, bar, or edge (Maffei *et al.,* 1974; Glezer *et al.,* 1976; Glezer *et al.,* 1977; De Valois, 1977b).
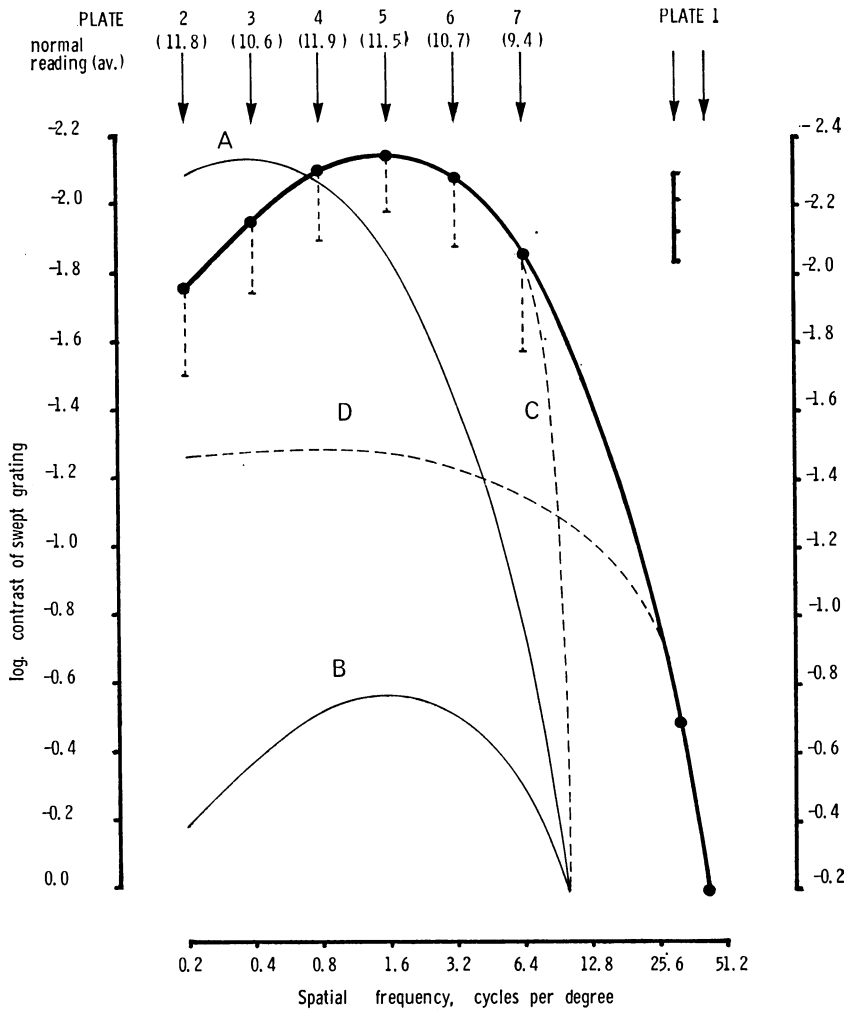
Fig. 2 *The Modulation Transfer Function, and how it can vary in disease. The heavy line is the MTF, and the ordinates give the contrast sensitivity, as determined on a TV display for swept gratings, and also using a standard psychophysical technique (method of ascending and descending limits—ordinate to R). The data points are at the frequencies tested by the grating book, and the error bars are 2 SDs of the determinations on the TV. The errors for the book are larger as can be appreciated by the inset scale, which shows contrast per vertical division of grating (cf. Table 2). Note that Plate 1 is not described in full in the text. The arrows at the top indicate where the printed gratings fit into the MTF. Curves A, B, C, and D represent ways in which the MTF is modified in disease*

Whatever the basic neurophysiological mechanisms underlying spatial analysis may be, the use of sinusoidal gratings has certainly shed considerable light on visual mechanisms in man. The effect of contrast on visibility is investigated by determining threshold contrast as a function of grating spatial frequency. Usually the reciprocal of threshold contrast, i.e., contrast sensitivity, is plotted and the graph so obtained is the *spatial frequency contrast sensitivity function* (CSF). It is often referred to as the (spatial) *modulation transfer function* (MTF). Such curves are plotted in Fig. 2. The standard normal curve is shown as a heavy continuous line. It is bell-shaped, and there is a peak at about 3 cycles per degree, which corresponds to the grating of Fig. 1 *A,* viewed at 85 cm. Such a grating is by no means a 'detailed' pattern, but it is at such a spatial frequency that contrast sensitivity is greatest:

a trained observer can detect contrasts as low as 0·3%. At higher and lower frequencies contrast sensitivity is much reduced. If the graph points are extrapolated to higher frequencies, the line cuts the abcissa. This intersection represents the spatial frequency at which a grating can only be seen if its contrast is 100%, i.e., black on white. Any grating of higher spatial frequency is indistinguishable from a uniform patch of grey. Thus this point on the MTF corresponds to visual acuity, as determined on a test type. The white gap between the two black arms of a Landolt C just visible to a person with 6/6 vision is 1 minute of arc. Maximum grating acuity is 30 to 40 cycles per degree. In practice it is difficult to obtain a sine wave grating with a contrast of 100%, for even the blackest inks reflect light. However, a black-and-white square wave grating has a contrast which is (mathematically) higher than

100%. Such factors explain the slight differences between the maximum acuity (in terms of visual angle) found by the use either of gratings or the various optotypes.

Thus, clinical acuity measures determine one point of the MTF, the intersection with the abcissa. It is as though, in testing hearing, the only point determined on the audiogram was the highest pitched tone that it was possible for the patient to hear. The graph of Fig. 2 illustrates the power of the grating method; it enables the whole spectrum of visual performance to be estimated, while acuity measurements determine only one extreme point. If such a measurement was able to characterise the entire curve, grating tests would have no clinical significance. However, as an observable fact the MTF may be modified in different ways, some of which are illustrated in Fig. 2. For example, the entire curve may be shifted to the left (curve *A*). In such a case the patient would complain of loss of visual acuity. The curve cuts the abcissa at 10 cycles per degree, corresponding to a visual acuity of 6/24. Such a loss is found in some cases of amblyopia (Hess and Howell, 1977). However, the normal curve could be shifted bodily downwards till the same loss of visual acuity occurred (curve *B*). This condition obviously represents a different and more serious visual loss and is approximated by other cases of amblyopia (Hess and Howell, 1977) and other organic disease (Arden and Gocukoglu, 1978). Curve *C* shows the case where visual acuity is lost preferentially for higher spatial frequencies. This occurs commonly in refractive errors (see below), while curve *D* shows the MTF of a patient who has lost contrast sensitivity to lower spatial frequencies. The visual acuity measured with a Snellen chart is normal, but vision is disturbed. Patients with such problems are found not uncommonly, as indicated above.

The reasons why the MTF may change in these different ways can best be understood if the significance of the various features of the MTF have been considered. The peak in the function is not found if experimental conditions are modified, and it appears that there is a mechanism which augments contrast sensitivity in the mid range. It is an inhibitory neural phenomenon, related to the mechanism which produces the 'Mach bands' (Robson, 1965; Kelly and Magnuski, 1975). The loss of such a neural mechanism could selectively depress the peak of the MTF curve.

Additionally, much physiological investigation has been directed to showing that the MTF is an envelope curve, produced by various subsystems. Thus it has been shown that, if a subject regards a grating of high contrast, taking care to move his eyes to avoid after images, his visual system adapts, so that his sensitivity to that spatial frequency is temporarily reduced. However, the sensitivity to gratings of other, different, spatial frequencies is unaffected (Blakemore and Campbell, 1969; De Valois, 1977a) or may be improved. In this way the concept has arisen of visual 'channels' each handling information about bands of spatial frequency. One channel can be inactivated (by adaptation) while others are unaffected. Visual impressions have been related to the relative sensitivities of the separate channels. Thus whether a low-contrast grating appears 'sine' or 'square' depends on whether the channel sensitive to the third harmonic is, or is not, activated (Campbell and Robson, 1968; Campbell *et al.*, 1969; Furchner *et al.*, 1977). Separate channels have been postulated for the processing of luminance and colour information (Regan, 1972, 1977). It has been shown that the channels are sensitive to the orientation of a grating and thus share this property with that of individual cortical cells (see for summary Robson and others in Spekreijse and van der Tweel (1977)). Physiological research is directed towards several questions. How do the channels interact? (Henning *et al.*, 1975; Furchner *et al.*, 1977; Campbell *et al.*, 1969). What is the relationship between signal intensity and channel output? (Blakemore and Campbell, 1969). What is the channel bandwidth? (Kulikowsky and King-Smith, 1973). How do channels develop during infancy? (Atkinson *et al.*, 1977). Such questions have obvious clinical relevance but are outside the scope of this article. There are, however, 2 further properties of the MTF which require description.

The concept of separate 'channels' for various spatial frequencies is in a sense a restatement of the fact that the retina is non-uniform. Only the fovea is specialised for high acuity and must therefore handle all information about high spatial frequencies. In the retinal periphery only lower-frequency channels are represented. The question immediately arises whether lower spatial frequencies are *preferentially* handled by the periphery. It is quite easy to demonstrate that practically this is the case by laying a mask, made of a piece of paper with a hole cut in it, in front of a low-frequency grating. If the hole subtends 0·5°, the subtense of the fovea, and the grating is of 1 cycle per degree or less, and of low (but suprathreshold) contrast, the grating cannot be seen through the hole. It does not help if the hole is moved to and fro across the grating. The effect is dramatic if the grating is luminous, for then the grating, invisible through the hole, can still be seen through the translucent paper. The question has been answered more formally by Hilz

and Cavonius (1974), Estevez and Cavonius (1976), and Howell and Hess (1978). For coarse gratings the central and more peripheral retina has an equal contrast sensitivity per unit area of retina, but the larger the retinal area stimulated (up to 45° for very coarse gratings) the greater the sensitivity. As a rough rule sensitivity increases with the number of cycles exposed up to the value of 6. For a 0·2 cycle per degree grating this corresponds to a visual angle of 30°. It is unlikely that this sort of integration can occur in the retina. The importance of this finding is that it implies that grating contrast sensitivity will be reduced in the presence of peripheral retinal disease, and therefore the use of a low-frequency grating provides a rapid check of peripheral retinal function. If there is peripheral damage (e.g., an arcuate scotoma) this should affect contrast sensitivity. Of course, the retinal locus of the lesion cannot be determined from such a test. The advantage is that it is rapid, and the test does not require that the patient maintains fixation, as is the case for all tests where the visual field is plotted.

Another advantage of grating tests is that the visibility of low spatial frequencies is not limited by the refractive properties of the eye. Readers who are wearing glasses will readily be able to test this by looking at the gratings of Figs. 1 and 3 with and without their spectacles. The effect of common aberrations of the optical system of the eye is preponderantly on the higher spatial frequencies, which pass through the system with a loss of contrast. Campbell and Green (1965) showed that if the optical system was bypassed, by forming laser interference fringes on the retina, contrast sensitivity was slightly improved for higher spatial frequencies, but considerable defocus did not alter contrast sensitivity for 1·5 cycles per degree. Curve *C*, Fig. 2, shows contrast sensitivity with a 1 D error of refraction. For a grating of 0·2 cycles per degree visibility is unaffected with more than ±15 D of aberration. Hence such a grating test immediately distinguishes patients whose visual losses cannot be cured by the prescription of spectacles from those who only have simple optical defects. This distinction is probably nearly universally applicable. Even localised lesions (e.g., eclipse burns) are unlikely to give no loss of contrast sensitivity at medium frequencies. Again, early lens changes can reduce contrast sensitivity, and the loss may be selective for low spatial frequencies (Hess, personal communication), so that acuity is scarcely affected, but such a condition will not be improved by a spectacle correction. In the bulk of cases where contrast sensitivity to coarse gratings is depressed there will be neuro-ophthalmological causes—retinopathies, retinal, optic nerve, or visual pathway damage due to a variety of causes. Thus, abnormalities of contrast sensitivity to low spatial frequencies all require specialised ophthalmological investigation, and a grating test would therefore be of use to non-specialists (general practitioners, opticians) in deciding whether referral was required.

It is sometimes considered that the ability to detect low frequencies is a function of different receptors, the rods. This is not the case. Rods do not contribute to the detection of very high spatial frequencies, since they are absent from the fovea. Detection of lower spatial frequencies is based on the activities of rods or cones, depending on the mean illumination. In scotopic viewing contrast sensitivity is low and confined to low spatial frequencies (Kulikowski and Kranda, 1977). Under photopic conditions, where contrast sensitivity to medium and low frequencies approximates to a maximum, rod activity is suppressed. Thus, in common forms of retinitis pigmentosa, even though the patient is completely night-blind, contrast sensitivity is normal. However, in those cases where there is cone involvement, defects in contrast sensitivity occur (Wolkstein *et al.*, 1978; Arden, unpublished).

Methods of producing gratings

Although for special purposes sinusoidal gratings can be produced by interference techniques (Campbell and Green, 1965; Green, 1970), in physiological work they are generated electronically on the face of oscilloscope screens. Various techniques have been described. They involve the use of several oscillators, which must be 'locked' together. Improper design will cause alterations in screen luminance, as spatial frequency is altered, or unpleasant beating effects occur. When low spatial frequencies are investigated, the subject must look at the screen through a low-power microscope or the screen must be very large (and expensive) to accommodate sufficient numbers of periods of the grating. It is difficult to obtain oscilloscope displays which are bright, and they have a decided green colour. In general, published designs are complicated, and not easily operated under clinical conditions. A convenient computer-driven display has been described, but is extremely expensive of computer time. An alternative technique is to produce gratings on a television display. The advantages are that the image is much larger and brighter, and the equipment is much less expensive. High-quality studio monitors are required to display small contrast differences, but they are not expensive, and have a much greater long-term stability than oscilloscopes.
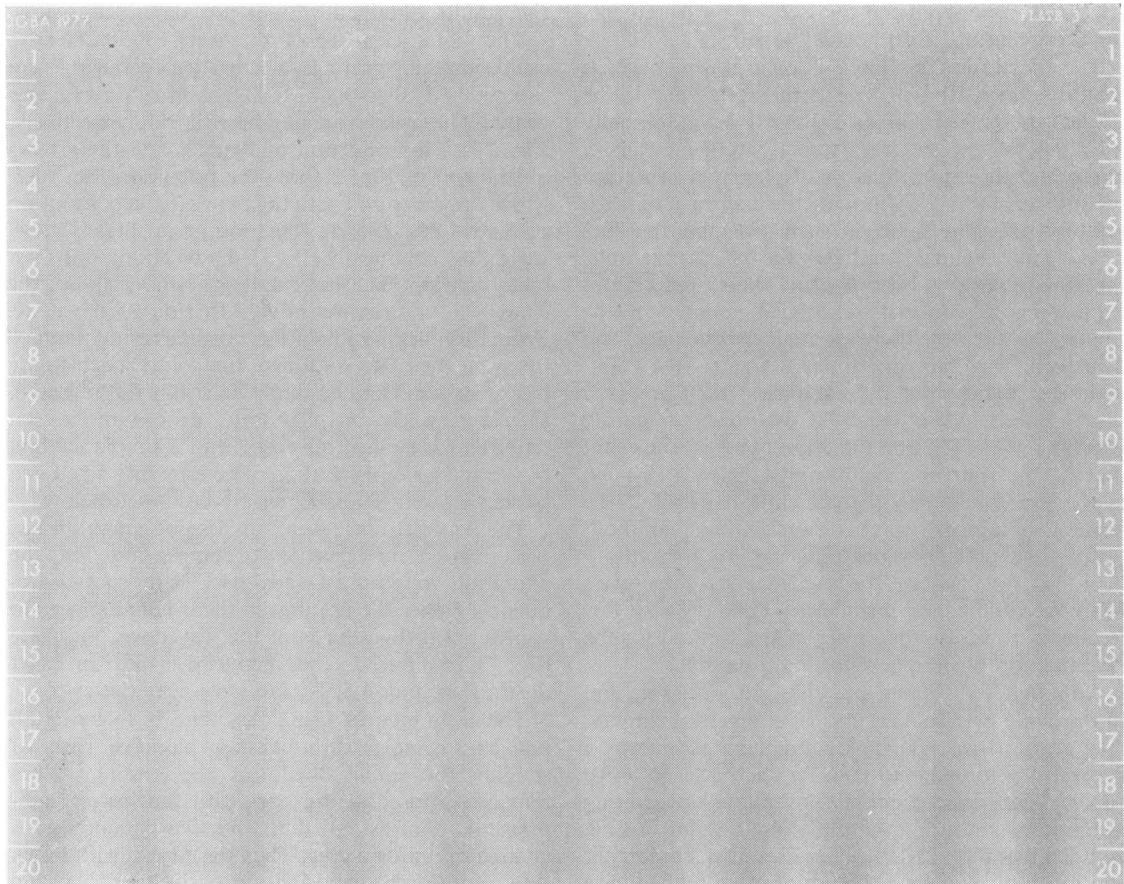
Fig. 3   A reproduction of Plate 3 of the grating book. In the original each division is 11 mm

The disadvantages are that there is a small residual flicker, and it is difficult to produce certain forms of display (oblique, drifting gratings) which might be required in experimental but not in clinical work. Subjects and patients both tolerate TV displays very well. Suitable equipment for use in clinical conditions has been described (Faulkner, 1978). Its use makes clinical testing simpler and more speedy.

Any clinical procedure for determining the threshold must be fairly rapid. In the laboratory the most precise methods, for example, forced-choice techniques, are the most time-consuming. It is thus better to ask a patient to increase or decrease the contrast of a display until the grating either appears or vanishes. (Naturally, the thresholds for these two conditions are not identical.) An alternative faster method (Fig. 3) is to use the form of display first realised by Robson (1965)—and see Campbell and Maffei (1974). A grating of a single spatial frequency is produced in which contrast varies in a direction parallel to the grating bars. If the graduation is sufficient, then the grating appears to vanish at some point on the screen. In theory, it would seem possible that the patient could merely indicate the point on the screen where the grating terminated. In fact, this is not a sharp endpoint, since the act of pointing alters the patient's perception. Additionally, with a large display, the screen is out of arm's reach. It is however possible to modify the contrast of such a display. If it is reduced, the grating appears to rise up the screen, while if contrast is reduced, the vanishing point becomes lower. The patient can be asked to adjust the display till the grating fills the top half of the screen, leaving the bottom half blank. The contrast threshold so obtained is not the same as that found with standard psychophysical techniques, but can be calibrated against them, and is simple and quick. The experimental points and scales in Fig. 2 show the

relationship between the two sets of measurements for a population of 50 normal persons.

The illustration in Fig. 3 is of a grating such as that described above. The contrast is said to be 'swept' in the vertical direction. It is additionally possible to 'sweep' the spatial frequency in a horizontal direction. Such a display was produced by Robson (1965). Although the contrast of each grating bar is the same, in such a display the bars do not look of equal length. On the left, for example, the low-frequency bars appear short, fading out soon because contrast sensitivity is low. In the centre, where medium spatial frequencies are displayed, the bars are longer, and to the right, with the higher spatial frequencies, they are very short indeed. Thus, each viewer instantaneously sees his own MTF, and the conception is so elegant that it has become widely known. Such a display, in theory, would be of great clinical use, but the results obtained were disappointing. Without instruction, patients reported a variety of results—they did not believe the evidence of their eyes. Moreover there are insufficient bars of very low frequency to utilise the power of the method for the investigation of peripheral retinal function.

Although TV systems are clinically utilisable and can provide precise measures of contrast sensitivity, they are not truly portable, and therefore it was a natural development to transfer the patterns on to paper. There are of course limitations to printing techniques, but, for example, colour vision testing with Ishihara or HRR plates is much commoner and much quicker than the use of more refined tests and is clinically acceptable and useful. Owing to imperfections in the original display, the limitations of the photographic process, imperfections in printer's plates and machinery, and imperfections in the surface of sheets of paper, it is technically very difficult to produce printed gratings which are of sufficiently high quality to be clinically useful. Usually even the best art prints contain numerous small flaws, which amount to defects in the reproduction of the higher spatial frequencies. However, the eye ignores such defects because the print contains a great deal of spatial information, contained in a large number of spatial frequencies. When a grating is printed, all the information is contained in one spatial frequency, usually lower than that of the imperfections, and the viewer at once picks up the flaws. An additional difficulty is that paper and inks have a semispecular reflection, and when low contrast gratings are viewed these reflections are very disturbing. The problem can be overcome, and the printed page protected, by enclosing the pages in plastic. A book containing such gratings has been produced, and

the results obtained with it are described below.

The book consists of 6 sheets, 305×280 mm, each containing gratings, which when viewed at 57 cm subtend 0·2, 0·4, 0·8, 1·6, 3·2, and 6·4 cycles per degree. These plates are numbered 2 to 7, respectively. Fig. 3 is a reproduction of Plate 3, and the arrows on the top of Fig. 2 show the points on the MTF which are measured with the plates (for a description of Plate 1 see below). The contrast on Plates 2 to 7 varies logarithmically (Fig. 3) by 0·088 log units per scale division. The inset scale on Fig. 2 shows the change in contrast-sensitivity/division of the plate. From this information, if the 'normal' result obtained by using the plate is known, the contrast sensitivity of any patient can be rapidly determined if required. However, such an elaborate procedure is not required for clinical purposes, and a simple method of use and a simple method of determining whether a patient's result is abnormal are described below.

The contrast on Plates 2 to 7 is not equal but has been varied to (partially) compensate for the alteration in contrast sensitivity with spatial frequency. Hence the gratings in the original appear to vanish about two-thirds of the way down the plate (Fig. 3 is reduced, and therefore is not an exact illustration, unless it is held very near the eye).

The technique of using the plate is to cover all but its lowest portion with a piece of card of roughly the same albedo as the grating. What remains exposed is the part with the lowest, subthreshold contrast, so that what the patient sees is an area of uniform grey. Then the card is withdrawn slowly upwards, exposing successively higher and higher contrasts, until the grating becomes visible. When the pattern first appears, it suddenly extends into regions which a moment before appeared a uniform grey. This is a demonstration of the fact that the grating is perceived with the integrative activity of relatively large retinal areas. The position of the card when the grating becomes visible gives the contrast threshold. An arbitrary scale is placed at the side of the plate, so that the position of the card can be read off. Although this technique is very simple, to achieve consistent results one must take several precautions. The patient must be properly instructed. Some patients fail to see low-contrast, low-frequency gratings until they are pointed out. They interpret the pattern as an adventitious shadow, or scalloping of the paper. Again, if patients have poor vision, the grating may be seen only as a series of blobs on one edge of the sheet, not as a series of indefinite stripes, and patients may not understand what is required of them. Because both the patient and the observer have to respond, the card must be withdrawn slowly, or else the position of the threshold readings will be

influenced by the combined reaction times. The higher spatial frequencies give the impression of being very fine lines (though they are not, as Fig. 2 shows) crowded together and difficult to see. Many patients require reassurance that the gratings are in fact visible half way down the page.

Other methods of administering the test were considered, and of course are possible. There are reasons for the procedure above which may not be obvious. If the high-contrast portion of the grating is shown to the patient, and the card moved downward till the 'invisible' portion is reached, a different threshold will be determined. The results obtained informally with this procedure did not seem as consistent. Furthermore, the patient, with this method, would be able to fix on a grating bar, and the resulting adaptation would be troublesome (Troxler effect). The card might be replaced by a mask consisting of a narrow window cut in a piece of card, so that only a small portion of the plate could be viewed at one time. This would, however, reduce the area of retina exposed to the grating and for coarse gratings would reduce the areal integration. The same objection could be raised against producing gratings which consist of a single spatial frequency but in which the contrast varied in steps. Plate 1 in the original book was of the MTF, but this proved unsatisfactory in use (see p. 204). It has been replaced by another, which consists of a form of near vision test, employing high contrast (30 and 100%) gratings of high spatial frequency, ranging from 10 to 50 cycles per degree. These enable the position of the high-frequency end of the MTF to be determined, and the two points on Fig. 2, and the arrows above labelled Plate 1, refer to these gratings. They may, in practice, be useful, to determine what a patient's visual acuity may be, without recourse to other equipment. Since they operate in an entirely different way, and were not used in the work described below, the gratings of Plate 1 are not described further.

Results with a normal population

The gratings described above were tested on a series of normal observers. Persons who were purchasing spectacles at an optician's premises were interviewed and asked if they would be willing to have an additional eye test. The tests were carried out by one trained observer (the author) and 4 other persons chosen because they had no medical training or experience of psychophysical measurements (they were in fact schoolgirls); 177 persons were tested in 1 week, all with their correct refraction. Results were discarded if (a) the corrected visual acuity was less than 6/6; (b) the subject or

Table 1

Patients rejected from survey*	
Glaucoma in family	5
Retrobulbar neuritis	1
Diabetes	1
Amblyopia, with reduced visual acuity	7
Old injury, with reduced visual acuity	5
Other CNS disease (various) with reduced visual acuity	5
Low visual acuity, cause undetermined	5
Grating scores statistically too low†	5
Grating scores statistically too high†	2
Total	36

*These cases were brought to our attention by the ophthalmic optician who had seen the patients, if visual acuity was below 6/6; some of the diagnoses were made after additional examination
†These results are + or − more than 3 standard deviations from the group mean

a close relation was known to suffer from glaucoma; (c) if the subject had diabetes; and (d) if the subject had ever suffered an attack of blurred vision lasting more than a few hours. No person in whom an ophthalmic optician had seen an opacity was tested.

The average results of those excluded was significantly higher (lower contrast sensitivity) than of the normal population. It was recognised that the questions asked of the subjects were insufficient to detect the presence of diseases which might affect contrast sensitivity. Thus, general hypertensive arterial disease can cause loss of contrast sensitivity (Arden, unpublished), and some cases of early cataract which scarcely affect Snellen acuity (Hess, personal communication). Again, after squint operations in childhood visual acuity may be preserved, but a loss of contrast sensitivity to lower spatial frequencies could remain (Weale and Arden, unpublished). For these reasons the collected results were analysed on a computer to determine whether they formed a homogeneous population. As a result 14 further observations were rejected. A summary of the rejected cases is given in Table 1.

The further analysis was carried out on a sample of 318 eyes. All tests were carried out in the same way. The patient was shown Plate 2, and the pattern described and pointed out. The nature of the task was described, and one practice run given. Then the right eye was tested, using Plates 2 to 7 in order. After a pause, to allow the occluded left eye to readapt to the lighting, it was tested in the same way, without any further practice run. No repeat observations were allowed. The ambient room lighting was supplemented with a desk lamp con-

Table 2 *Inter-observer variability*

	Observer*									
	1		2		3		4		5	
	mean	SD	mean	SD	mean	SD	mean	SD	mean	SD
Cycles/degree										
0·2	11·9	2·7	12·7	1·8	12·9	1·5	13·5	1·6	13·7	1·8
0·4	10·6	1·5	11·1	1·7	12·0	1·4	11·9	1·7	11·5	1·7
0·8	11·9	1·4	12·6	2·0	13·0	1·2	12·9	1·8	12·6	2·4
1·6	11·5	1·6	12·4	2·0	12·7	1·6	13·1	1·4	12·3	2·0
3·2	10·7	1·8	10·1	2·1	11·5	1·7	11·8	1·5	10·3	2·4
6·4	9·4	1·8	7·7	2·5	10·3	2·2	10·7	1·4	9·4	2·5
Total score	66·0†	7·2	66·8†	10·0	72·5	7·1	74·0	7·4	70·0	10·5

*Observer 1 was experienced in administering medical and psychophysical tests; the others were not. The numbers in the body of the Table are the threshold readings from the scales on the test plates
†There is a highly significant difference between these 2 total scores and the values obtained for the other 3 observers
  Note that all values are approximately 0·5 divisions higher than obtained with other grating samples

taining a 60-W incandescent bulb, held 16 inches (40 cm) above the surface of the table on which the book was placed. The trial showed a number of points. It is simple for the general population. No one had any difficulty. The untrained operators had no difficulty in administering the test. It took them about 6 minutes, including writing down the patient's details, the test results, and ushering the patient into and out of the test room. The results obtained with right and left eyes were identical. Thus, within the limits of the test procedure learning does not appear to play a part. However, informal testing has since shown that if a naive observer is repeatedly tested for several hours his results do improve. Moreover, the testers all noticed that they could see the gratings before the patients responded. In the age range 11 to 70 there was no influence of age on the results, grouped in decades of age. However, this grouping may conceal a reduction in contrast sensitivity which occurs in early adolescence, for (Weale and Arden, unpublished) a group of children aged 9 to 13 gave significantly better results than the adult population. In the survey described here the extremes of age were underrepresented.

Table 2 shows the readings obtained by the 5 observers for the various test plates. It should be mentioned that the books they employed were of a slightly different quality (owing to the plastic used) to later copies, and all the scale figures are higher than would subsequently be obtained by about half a scale division. Table 2 shows that there are systematic differences obtained between the 5 testers, who were working under comparable conditions. These may be attributed to factors such as the clarity of the tester's instructions to the patient, and the personality of the tester, which affects the criterion adopted by the patient in making a threshold judgment.

DEFINITION OF AN ABNORMAL RESULT
Table 2 shows that there is a considerable variance among the normal population, and a variability among test persons. The definition of the limits of normal therefore poses certain difficulties. There is no reason to suppose that very low-scale readings (implying a very high contrast sensitivity) are associated with disease. It is more probable that the test fails in such a case because the patient makes random guesses. When an exceptionally high reading is encountered in a patient who otherwise, for other plates, achieves good sensitivity, the most likely explanation is that during that particular test the patient was inattentive. This can be checked very simply if the test is repeated, but in the series described above this was not done, both to avoid bias and to make the test as simple and as quick as possible. Although it is likely (Blakemore and Campbell, 1965; Bodis-Wollner, 1972; De Valois, 1977b; Kulikowsky and King-Smith, 1973) that the spatial frequencies tested by the plates form several 'channels', a possible method of minimising patients' errors is to sum all the scale readings for Plates 2 to 7, achieving a final 'score'. The variance of the scores is proportionately considerably less than the variance for individual plate scale readings.

In practice it has been found that the patient's score is a reliable indicator of the presence or absence of abnormality. Another indication of abnormality is asymmetry of results between the 2 eyes. No subject should have an interocular differ-

Table 3 *Indications of abnormality (applicable for an observer who obtains an average score, from a normal population, of 62–66)*

Highest permissible reading on any one plate	16
Score probably indicates abnormality	78–82
Score indicates abnormality	>82
Interocular difference of scores indicating abnormality	>11

ence greater than 11. Table 3 shows the values used at present by the author to determine the limits of normal. The difference between the average score and the limit of normal (20) implies a tolerable variation of 3·3 scale divisions on the plates. Reference to Fig. 2 gives the equivalent change in contrast corresponding to such a variation (the inset scale). It can be seen that this is larger than the dotted lines extending from the data points, which correspond to 2 standard deviations from the mean. However, these data points were obtained with a TV display from 50 normal subjects who had either technical or medical experience. Experience of using the test (Arden and Jacobson, 1978) suggests that the values given in Table 3 are fairly conservative, but it is not possible to use the data of Fig. 2 and Table 2 to estimate the proportion of false negative and false positive test results for various definitions of abnormality.

CLINICAL RESULTS ON ABNORMAL EYES
The book of gratings has been used intensively in specialised ophthalmological clinics for 6 months, and contrast sensitivity has been found to be reduced in a variety of pathological conditions. The following 3 examples are given to illustrate that the test can elucidate important information even when the patient is under specialist care.

Case 1. An unmarried woman aged 77 was seen on 15 June 1977. She had been attending since 26 November 1975, when she complained of a black spot before the right eye, which was found to be a small altitudinal field defect extending to within 2° of the fovea inferiorly. There were additional complaints which suggested temporal arteritis, and the diagnosis of giant cell arteritis was confirmed by biopsy. There was evidence of a small infarct at the right disc, and fluorescein angiography of the right fundus showed slowing of circulation. Eighteen months later the field defect persisted, visual acuity was 6/9 corrected in either eye, and the diagnoisis was of a unilateral neuropathy. The grating results were:

c/degree	0·2	0·4	0·8	1·6	3·2	6·4	Total
Right eye	14	14	15	16	17	14	90
Left eye	16	13	14	15	14	16	88

Since both eyes gave abnormal results the records were re-evaluated. At the time of admission it was noted that both temporal arteries were abnormal and retinal arteries in both fundi were attenuated. In the right eye the infarct at the disc margin was evident, but in the left eye, in a corresponding position, there were cotton-wool spots slightly removed from the disc. Although these were later disregarded, and no field defect found in the left eye, it is likely that this lady had bilateral disease, and although no scotoma developed in the left eye this was sufficient to cause a loss of contrast sensitivity.

Case 2. A man aged 32 noted a transient blurring of vision in the left eye while working on an oil rig. It completely cleared in less than 2 weeks. Three months later, on leave, he mentioned this to his dentist and was referred to an ophthalmic clinic. He stated his vision was entirely normal, and on close questioning no significant history was disclosed. On examination vision was 6/5 in both eyes, HRR plates were read normally, there was no afferent pupillary defect, and the discs were within normal limits. There was no field defect. The grating test showed:

c/degree	0·2	0·4	0·8	1·6	3·2	6·4	Total
Right eye	11	11	13	12	10	7	64
Left eye	16	14	15	13	13	10	81

Thus, the contrast sensitivity in the left eye is abnormal, and the evoked potential to pattern in that eye showed the delay characteristic of demyelinisation.

Case 3. A man aged 52 had a long history of dysthyroid eye disease, which had been treated medically and also by radiotherapy. Although he still suffered from proptosis, his thyroid condition was controlled, and he did not suffer, with adequate correction, from diplopia. Intraocular pressure was normal, fundoscopy was normal, and visual acuity (corrected) 6/9 in both eyes. The grating test results were:

c/degree	0·2	0·4	0·8	1·6	3·2	6·4	Total
Right eye	16	17	19	19	19	16	106
Left eye	19	17	19	—	Not seen*	—	130*

*We arbitrarily assign a reading of 25 if the grating is invisible

Since this result was so abnormal, static perimetry was performed with a Goldmann perimeter, and generalised constriction of the fields was found to 20 to 30°. The patient worked as a taxi driver. Apart from the field loss the loss of contrast sensitivity implies that his visual sensation was similar to that

of a normal person driving in a thick fog. The loss of visual function was possibly a sequela of the radiotherapy.

Such a list could be extended. There have been several published accounts of losses of contrast sensitivity in other conditions. Most authors have employed oscilloscope displays. Bodis-Wollner (1972, 1974, 1975, 1976) and Bodis-Wollner and Diamond (1973) have described losses of contrast sensitivity in patients with vascular, neoplastic, and inflammatory intracranial lesions. Loss of sensitivity to a relatively narrow band of spatial frequencies, with no, or minimal, loss of visual acuity can occur. Changes in contrast sensitivity can be used to follow the change in the patient's condition. Study of the change in the MTF provides evidence about the bandwidths of the 'channels' handling spatial information.

Sjøstrand and Frizen (1977) have investigated contrast sensitivity in macular disease, and have described considerable loss of low-frequency sensitivity with minimal loss of visual acuity. Although only a small number of patients have been examined, they conclude that visual acuity is a poor way of describing the visual problems of their patients, and that contrast sensitivity is an important tool for detecting early disturbance.

Hess and Howell (1977, 1978); Hess (1977); and Howell and Hess (1978) have investigated contrast sensitivity in amblyopes, and have shown that a dual classification is possible—those with and those without loss of low-frequency contrast sensitivity. Contrast sensitivity may be lost even though visual acuity is normal. Freeman and Thibos (1975) and Fiorentini and Maffei (1976) have shown that myopia and astigmatism can lead to developmental defects detectable by grating tests. Regan *et al.* (1978) have investigated contrast sensitivity in patients suffering from multiple sclerosis. In 33 of 48 patients the MTF was abnormal. In 20 the abnormality was qualitatively different from that produced by refractive error, and there was no firm clinical evidence for visual involvement. It is suggested that the test discloses 'hidden visual loss' and would aid the diagnosis of multiple sclerosis. The grating book has been used in 2 completed investigations. Arden and Gocukoglu (1978) reported on 57 cases of retrobulbar neuritis. In patients with multiple sclerosis 95% showed abnormality in the affected eye and 60% in the 'unaffected eye'. In patients with no evidence of multiple sclerosis 29 of 36 had abnormal grating tests, in 7 cases bilaterally abnormal. In a subgroup of 24, with minimal disturbance, it was found that grating abnormality was a superior indicator of disease to the cortical evoked potential, previously considered the most sensitive test avail-

able. The results are compatible with those of Regan *et al.* (1978).

Arden and Jacobson (1978) report on 50 cases of glaucoma, including 7 without field loss. Grating tests were abnormal, and the degree of abnormality varied with the grading of the disease. It was suggested that the grating test would be suitable for screening for glaucoma, since it could detect abnormality not disclosed by any field screener.

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