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AGE-RELATED NORMS FOR THE CAMBRIDGE LOW CONTRAST GRATINGS, INCLUDING DETAILS CONCERNING THEIR DESIGN AND USE

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Summary—1. The Cambridge Low Contrast Gratings provide a simple, inexpensive but reliable measure of contrast sensitivity at a spatial frequency close to that at which the normal human visual system is maximally sensitive.

2. The range of contrasts is sufficient to avoid ceiling and floor effects with normal observers and with patients, and the change in contrast from one grating to the next is small enough to avoid spuriously high or low estimates of contrast threshold.

3. Test scores show consistency from one laboratory to another. The test takes less than 5 min to administer, but it commonly reveals deficits present in diabetes, multiple sclerosis, optic neuritis and glaucoma amongst patients who have normal Snellen letter acuity.

4. The incidence of these deficits is higher in young patients than in the middle-aged or elderly.

5. From the twenties onwards, contrast sensitivity scores for the normal population decline with age by about 10% for each decade of life. The average decline over the life span is similar to the range of sensitivity within the normal population at any given age.

Key words—Contrast sensitivity; glaucoma; diabetes; multiple sclerosis; optic neuritis; scopolamine; Snellen letter acuity.

INTRODUCTION

The Cambridge Low Contrast Gratings have been designed for observers who have normal (or corrected-to-normal) Snellen letter acuity. The gratings assess contrast sensitivity at a spatial frequency of 4 c/deg.

DESIGN CRITERIA

The test was designed with several criteria in mind. In order to make these criteria explicit they have been numbered separately in the paragraphs which follow.

(1) The Snellen chart needs augmenting rather than replacing. The chart provides a useful clinical test that is cheap, rapid to administer, and easy to undertake. It is perfectly suitable for use in refracting a patient and it can detect abnormalities in a significant proportion of patients with ocular and retrobulbar disease. Given these properties the test is unlikely to be superceded. Nevertheless many patients have normal letter acuity but complain of defective vision. A simple means of detecting their impairments would be clinically useful.

(2) The contrast sensitivity function in patients with normal letter acuity will be relatively unaffected in the high spatial frequency range. (Although there are circumstances in which the Snellen letter acuity and grating acuity differ, they are in our experience highly correlated.)

(3) Despite normal letter acuity and normal contrast sensitivity at high spatial frequencies, sensitivity may nevertheless be reduced at spatial frequencies close to 4 c/deg. In a range of retinal and optic nerve diseases, including diabetes, glaucoma and multiple sclerosis, it has been shown that contrast sensitivity is usually affected at spatial frequencies close to 4 c/deg (Hyvarinen *et al.*, 1983; Ross *et al.*, 1984; Zimmern *et al.*, 1979).

(4) Testing time is limited, and (5) it is better to measure contrast sensitivity at one spatial frequency well, than to spread the testing effort over several spatial frequencies, particularly (6) those that may be less likely to reveal impairment.

It is essential (7) to separate the willingness of an observer to report weak sensations (his crite-

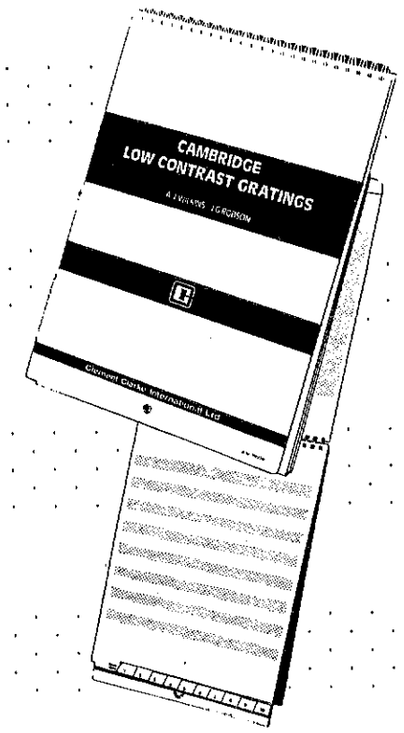

Fig. 1. A reproduction of part of Page 7 from the Cambridge Low Contrast Gratings. The stripes are shown actual size, although the size of the dots, and therefore the contrast of the stripes, may have been altered slightly in the process of reproduction. When viewed from a distance of 6 m the stripes are on the borderline of visibility for most observers. Pictures of the booklet when closed and open are superimposed.

rion) from his ability to detect them (his sensitivity), and the psychophysical method of two-alternative forced choice is a suitable method for doing so. This powerful psychophysical procedure is (8) minimally affected by observer bias, or (9) by lapses of attention and yet (10) is very simple for patients to undertake.

Any test that is to be used for screening must not only be quick and simple to undertake, but (11) cheap, (12) portable, and (13) simple to administer. Conventional cathode ray tube techniques are neither cheap nor portable. Any alternative technique must provide for (14) mass reproduction (15) in a medium that does not deteriorate, using (16) a high level of quality control so that variations from one version of the test to the next are minimised.

Because patients with multiple sclerosis have been reported as showing orientationally-selective sensitivity deficits (Regan *et al.*, 1980; Coupland and Kirkham, 1984; Kupersmith *et al.*, 1984), the test should (17) be able to measure contrast sensitivity over a range of different orientations.

IMPLEMENTATION OF THE DESIGN AND SATISFACTION OF THE CRITERIA

The Cambridge Low Contrast Gratings were designed to satisfy the above criteria as closely as possible. In this section, the descriptions of aspects of the design are followed in parentheses by the design criteria, as numbered above.

The Gratings are presented in an A4 size (210 × 295 mm) booklet, spiral bound along the shorter edge. The booklet is hung on a wall at a viewing distance of 6 m. The pages are presented in pairs, one above the other. One page in each pair contains a grating and the other is blank but has the same mean reflectance. A grating is illustrated in Fig. 1. The patient is simply required to choose which page, top or bottom, contains the grating. The pages are turned revealing gratings with lower and lower contrast, positioned randomly on the top or bottom page (7–13). The gratings are usually shown with stripes horizontal but, if necessary, the book can be turned so as to test sensitivity at any other orientation (17).

The gratings are printed using conventional techniques which keep the cost down and ensure a high standard of consistency from one test to the next (11, 14–16). The laminated card on which the gratings are printed is a good Lambertian reflector and so the contrast is little affected by the angle of incident illumination. Unless the booklet is left open in sunlight the gratings will not deteriorate as a result of prolonged exposure to light because one page shields the next (15). The surface of the card is laminated with clear matt plastic so that it can be wiped clean (15).

Contrast sensitivity is assessed at one spatial frequency only: that at which abnormalities are most common (Hyvarinen *et al.*, 1983; Ross *et al.*, 1984; Zimmern *et al.*, 1979) (3–6). The gratings have a square-wave rather than sine-wave luminance profile because it is technically simpler to generate (14–16). Sensitivity to a sine-wave profile can be predicted from that to a square-wave. At a spatial frequency of 4 c/deg the higher harmonics present in the square-wave grating do not contribute to its visibility at threshold contrast (Campbell and Robson, 1968). Sensitivity to the third harmonic (at 12 c/deg) would have to be about three times that at 4 c/deg because the third harmonic has one third the amplitude of the fundamental. In practice sensitivity at 12 c/deg is rarely if ever greater than that at 4 c/deg, even in patients with abnormal vision, as inspection of the data given in the above references will confirm. The sensitivity to the square-wave is therefore similar to that for a sine-wave with contrast equivalent to the fundamental component of the square-wave; i.e. a sinusoid with a peak-peak contrast 1.27 times that of the square-wave.

JUSTIFICATION FOR THE USE OF ONE SPATIAL FREQUENCY

The Cambridge gratings were designed to augment rather than to replace the Snellen chart, and to be used with observers who have normal (or corrected-to-normal) Snellen letter acuity. Snellen acuity is dependent upon sensitivity mainly at the upper spatial frequency end of the range of the contrast sensitivity function. Observers with normal Snellen acuity would therefore be expected to show relatively normal sensitivity at the high frequency end of the range. Given that testing time is limited, it was decided to avoid the high spatial frequencies and concentrate measurements instead at a spatial frequency near the peak of the contrast sensitivity function, a frequency at which deficits had commonly been reported in diseases such as multiple sclerosis (Regan *et al.*, 1977), diabetes (Hyvarinen *et al.*, 1983) and glaucoma (Ross *et al.*, 1984). It is uncommon for sensitivity loss to occur selectively over a limited range of spatial frequencies (Regan *et al.*, 1977; Kupersmith *et al.*, 1983): diffuse loss is the most consistent pattern, but with greatest loss for spatial frequencies near 4 c/deg (Zimmern *et al.*, 1979). Selective deficits at high spatial frequencies would be expected to be associated with a loss of Snellen letter acuity, and selective deficits at low spatial frequencies are rare: only 3/48 patients in Regan's (1977) series showed deficits of this kind. Although Bulens *et al.* (1986) reported certain patients with Parkinson's disease as showing a loss at spatial frequencies near 0.8 c/deg the proportion for whom such loss was confined to this spatial frequency was small.

HISTORY OF THE DESIGN OF THE CAMBRIDGE GRATINGS

The first version of the gratings was described by Della Sala *et al.* (1984). In this version the gratings were generated by ruling fine, closely-spaced parallel lines using a computer graph plotter. The spacing between successive lines was varied periodically. At a viewing distance of

6 m individual lines were invisible but the variations in line spacing could be seen as fluctuations in line density, and these comprised a grating with a square-wave luminance profile and a spatial frequency of 4 c/deg.

The technique used by Della Sala *et al.* was demonstrably effective in clinical practice, but the consistency from one reproduction of the test to the next was not high. With the advent of programmable dot-matrix printers it became possible to generate the gratings by varying the spacing of dots rather than lines. Using this technique less ink is deposited on the paper and greater control over contrast variation can be achieved. (The technique differs from that used in conventional printers' screens in so far as the dots always remain separate and of constant size.)

In the published version of the test bands of dots alternate with bands of unprinted paper to form gratings. The dots have been reproduced from originals generated by the pins of a dot matrix printer controlled by computer. Part of one of the pages is reproduced actual size in Fig. 1. The dot density within the bands decreases from one grating to the next, thus reducing the contrast. The blank pages comprise a matrix of uniform dots with a density half that of the bands of the grating. The blank pages therefore have a space-averaged reflectance identical to that of the gratings.

CALIBRATION

Photometric measurements of the printed gratings were taken under conditions of typical office illumination: i.e. ceiling-mounted fluorescent tubes. (The tubes were driven by solid state circuity at a frequency of 20 kHz so as to provide stable illumination.) Light was directed without lenses via a matt black tube (500 mm long, 9 mm wide) onto an eye-response corrected current biassed silicon photodetector (Centronic OSD 100-P). The distance between the page and the open end of the tube was sufficient to avoid shadows. A comparison of the output of the photodiode when the tube was directed at dotted and undotted portions of the page provided a measure of the contrast of the grating.

The contribution of scattered light in reducing the measured contrast was assessed by directing the detector first at a strip of white paper of width similar to the bars of the grating and then at a black "surface" of similar dimensions (the aperture in an opaque sphere) positioned immediately beside the paper. The contrast between the two surfaces was greater than 99%, suggesting that the contrast measurement was not appreciably affected by stray light. The variation in contrast from one copy of the test to the next was smaller than the variation in measurement.

Contrast measurements were most reliable from the grating with the highest dot density (the "Demonstration" grating) and measurements were therefore concentrated on this grating. The contrasts of the remaining gratings were calculated from these measurements and a knowledge of the dot densities. All but three of the gratings had contrasts too low to be measured directly, but where the contrasts were sufficient, the measurements obtained agreed well with the calculated estimates.

The above method of calibration relies on the fact that the dots do not overlap, and the average size and reflectance of a dot is independent of dot density.

TEST PROCEDURE AND SCORING

Originally the entire set of plates was simply presented in order of descending contrast a total of three times to each eye in turn. The total number of errors on the weaker eye was noted and compared with standardised norms obtained from age-matched normal observers. The procedure was more time consuming than necessary, and when the test was published a revised procedure was recommended.

The recommended procedure is to show the pages in order of descending contrast, as before, but to stop when the first error is made. Four descending series are shown separately to each eye. When the first error is made or the end of a series is reached, a new series is begun. The second and subsequent series are commenced, not from the first grating, but from the one four previous to that on which the last error was made. For example, on the first series an error might be made on page 9; the next series would commence at page 5, and so on. This procedure reduces the number of stimuli presented, and concentrates measurements on gratings with contrasts close to threshold. It could, in principle, result in an identical sequence of choices on all four series. However, it will become evident from the normative data presented later that, in practice, the variability in the response near threshold is sufficient to ensure that each

new series is usually begun at a page different from that on which the previous series commenced. As a result, the sequence of choices that the observer makes is rarely the same.

Grating No. 11 has a contrast that is below the threshold of most normal observers, and it is recommended that, in clinical practice, this grating is excluded in order to save time. If no error occurs on the last grating (No. 10), an arbitrary score of 11 is given. The four numbers are added together and their sum converted to contrast sensitivity using a table provided with the test.

It will be noted that this procedure truncates the scale: it makes the implicit assumption that an error would have been made on grating No. 11, had it been tested. Of course, this assumption is unjustified. Even were observers to find it impossible to discriminate the grating, the probability of a correct response would still be 0.5 by chance. The truncation that the scoring procedure entails has little consequence in clinical practice when observers with abnormal contrast sensitivity are to be compared with controls. However, if the gratings are to be used to discriminate between normal observers under various experimental conditions, alternative test procedures may be necessary, possibly including the use of Grating No. 11. One suitable procedure is to present all the high-numbered gratings repeatedly in random order and to fit an ogive to the function relating the probability of a correct response to grating contrast.

As mentioned above, the recommended testing procedure involves the addition of the scores of four trials. The averaging that this scoring procedure entails is based on the assumption that during these trials the observer's criterion remains reasonably stable. In certain clinical conditions (e.g. optic neuritis) the patient's threshold is abnormally variable (Foster, 1986). If it is necessary to estimate this variability, rather than simply to show that, on average, a patient's performance is abnormal, it is advisable to use an alternative testing procedure that allows the estimation of the steepness of the frequency-of-seeing curve, as described in the next section.

If the recommended clinical test procedure is used, the total test scores can be converted to contrast sensitivity by means of the conversion tables published with the test. The conversion tables were generated by assuming that when an observer correctly detects a grating on three out of four occasions his contrast sensitivity is equal to the reciprocal of the contrast of that grating; intermediate scores were linearly interpolated.

An alternative way for converting test scores to contrast sensitivity is via the graphs shown in Fig. 2. These graphs were derived by calculating the expected test score for ideal observers, as will be described in the following section. The conversions obtained using Fig. 2 differ slightly from those given in the published conversion table.

The contrasts of the 12 gratings range from a maximum for the "Demonstration" grating of 0.13 or 13%, to a minimum of 0.0011 or 0.11% for Grating 11. At the high-contrast end of the range the gratings decrease in contrast by relatively large steps, but below 1.0% the contrast between successive gratings differs by a constant factor: the reciprocal of the square-root of two. Figure 3 illustrates this progression.

THE FREQUENCY-OF-SEEING CURVE

To determine whether the change in contrast from one plate to the next was sufficient to measure small changes in threshold, a mathematical model of the test was developed, based on the work of Foley and Legge (1981). Foley and Legge measured the contrast sensitivity of two normal observers to sinusoidal gratings at spatial frequencies of 0.5, 2.0 and 8.0 c/deg using two-alternative forced choice. They found that the probability of a correct response (p) as a function of contrast (C%) was well fit by the following expression due to Weibull (1951) from Quick (1974)

$$p = 1 - 0.5 \exp(-a\, C^b). \qquad (1)$$

When plotted against linear contrast the function approximates the familiar S-shape of the psychometric function; the shape is distorted when plotted against log contrast as in Fig. 4. Foley and Legge reported the greatest sensitivity at 2 c/deg, at which frequency the parameter b had a value close to 3 and the parameter a a value close to 50. Figure 4 shows that the parameter a influences the x-position of the curve, and the parameter b its steepness. The lower sensitivity at the other spatial frequencies was reflected only in the parameter a: the parameter b remained approximately constant. In other words, the changes in sensitivity influenced the x-positions of the frequency-of-seeing curves, leaving their steepness unchanged.

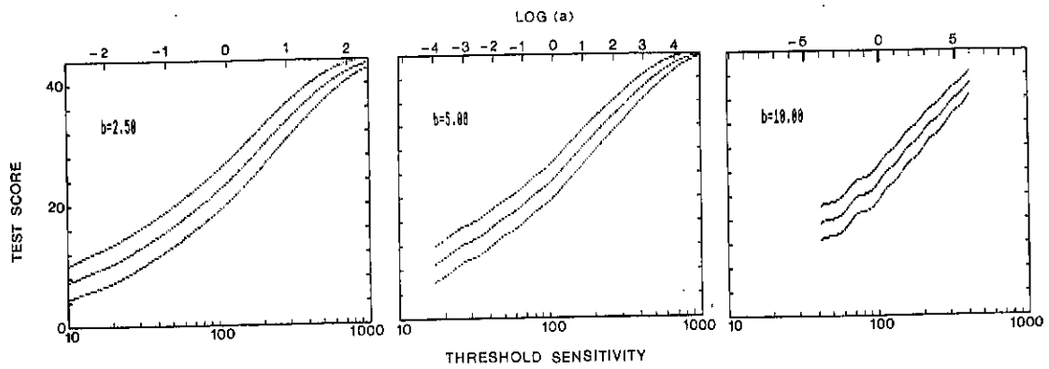

Fig. 2. The relationship between threshold contrast sensitivity and test score on the Cambridge Low Contrast Gratings, as calculated using the Quick (1974) function: probability of correct response $= 1-0.5\exp(-a\cdot C^b)$ which is graphed in Fig. 4. The value of the parameter b was held constant and a value of parameter a selected such that the probability of a correct response was 0.75 (i.e. threshold in two-alternative forced-choice) when $1/C\%$ took a value shown as "threshold sensitivity". With parameters a and b taking these values, the probability of a correct response on each of the Gratings was calculated on the basis of the contrast ($C\%$) of the grating. These values were then used to calculate the expected score for the test, and the standard deviation of that score. The central curve in each figure shows the way in which the expected score varies with the contrast threshold of the ideal observer. The flanking curves show ± 1 SD. In (a) the parameter of b takes a value of 2.5, a value typical for inexperienced observers. In (b) the value of b is 5.0, which is considerably higher than usually obtained, even with experienced observers. The curves are nevertheless very similar to those in (a). In (c) b takes an unrealistically extreme value of 10.0 in order to show the scalloping which results when the psychometric function is insufficiently sampled.

For a range of different values of the parameters a and b, equation (1) was used to determine the probability of a correct response on each of the 12 plates of the Cambridge Low Contrast Gratings. The probabilities so obtained were then used to calculate the test score expected from the recommended test procedure (described in the previous section), and the standard deviation of that score. In Fig 2 the mean test score and its standard deviation are shown as a function of the parameter a, for representative and extreme values of b. As already mentioned, the parameter a influences the x-position of the psychometric function and thus the contrast threshold (i.e. the contrast of a grating for which the probability of a correct response would be 0.75–midway between a chance response, probability 0.5, and a certain response, probability 1.0). The reciprocal of the threshold, the "threshold sensitivity", is therefore shown below the numerical value of a.

When the value of b is close to that reported by Foley and Legge, the psychometric function is not steep (cf curves A, B and E in Fig. 4) and there are several test plates for which the probability of a correct response is greater than 0.5 (chance) and less than 1.0 (certainty). Under these circumstances the curve relating the observer's sensitivity to test score is smooth. As the value of parameter b increases, the psychometric function becomes steeper until it is so steep (cf curve D in Fig. 4) that the probability of a correct response on each plate is either nearly 0.5 or nearly 1.0. Depending on the x-position of the curve, there may be no gratings for which the response probability is close to 0.75. Under these circumstances the function relating test

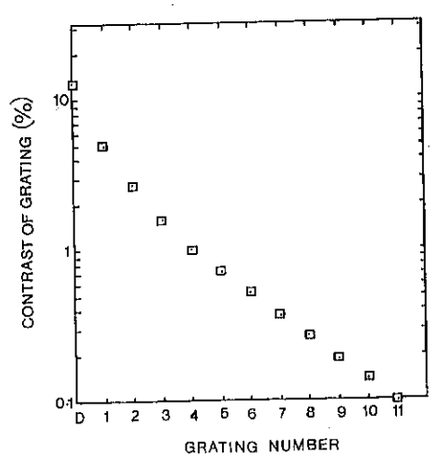

Fig. 3. The contrast of the Cambridge Low Contrast Gratings. The first few gratings differ in contrast by relatively large steps. Gratings numbered 5 and above differ by a factor equal to the reciprocal of the square-root of 2.

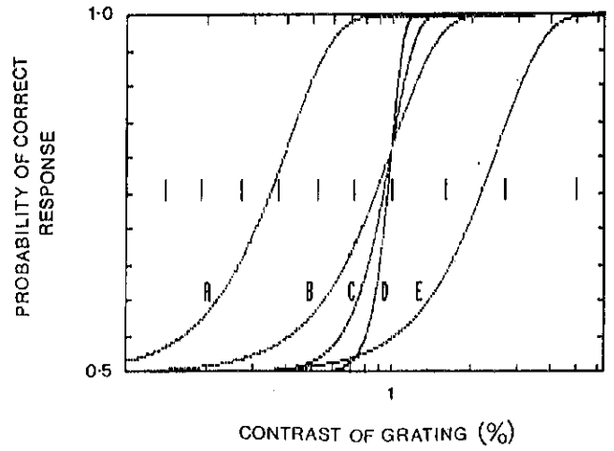

Fig. 4. Graphs of the Quick (1974) function. Curves (A), (B) and (E) have values of parameter a of 10, 1 and 0.1 respectively. The value of parameter b is 2.5. Note that the curves have different x-positions, but similar steepness. The curves (B), (C) and (D) have values for parameter b of 2.5, 5 and 10. The value of a is 1. Note that the curves have similar x-positions, but different steepness. The contrasts of the Cambridge Low Contrast Gratings are shown by short vertical lines across the centre of the graph.

score to the observer's sensitivity shows a scalloping, most marked in Fig. 2(c).

Scalloping such as that in Fig. 2(c) appears only when the values of b are uncharacteristically extreme. It is hardly seen for values of b considerably larger than those reported by Foley and Legge. However, these authors used forced choice between two successive intervals and provided feedback, and it is conceivable that parameter b may take a different value when a choice is made between two simultaneously visible stimuli without feedback, as in the Cambridge Gratings. For this reason the Gratings were repeatedly shown to two observers in an attempt to obtain a realistic estimate of the value of the parameter b. The observers, male, aged 24 and female, aged 22, both had 6/5 vision and were tested monocularly. They were repeatedly shown pages 5–11 from the Low Contrast Gratings, in random order and random position, more than 40 times each. The proportions of trials on which a correct response occurred were used to estimate the values and a and b by fitting equation (1). For the first subject, who was tested in one session, the values obtained were $a = 4.57$ (SE 1.19), $b = 2.58$ (SE 0.66), mean deviance 0.46, ($\chi^2 = 2.18$, d.f. $= 5$, $0.9 > P > 0.8$). For the second subject, who was tested in two sessions, the values were $a = 3.97$ (SE 1.19), $b = 1.40$ (SE 0.30), mean deviance 1.77 ($\chi^2 = 8.84$, d.f. $= 5$,$0.2 > P > 0.1$) for the first session and $a = 29.67$ (SE 22.5), $b = 2.63$ (SE 0.63) mean deviance 0.97, ($\chi^2 = 4.83$, d.f. $= 5$,$0.5 > P > 0.3$) for the second. The values for b are close to those obtained by Foley and Legge (1981); the values of a indicate a poorer contrast threshold, which might reflect the effects of field size and display luminance. The values of b are well within those for which the functions in Fig. 2 show no obvious scalloping. The values of b obtained with patients are unlikely to be higher, and can be lower than those for normals (Foster, 1986). These considerations suggest that the spacing of the contrast steps in the Cambridge Low contrast gratings is sufficiently small to avoid any biassed estimates of contrast sensitivity, such as those revealed by scalloping in Fig. 2.

NORMATIVE DATA, TEST RELIABILITY AND SENSITIVITY

Della Sala *et al.* (1987), using the unpublished version of the test, examined a total of 74 normal observers, all of whom underwent a routine ophthalmological examination including Snellen acuity, slit-lamp examination, tonometry and ophthalmoscopy. All subjects had normal or corrected-to-normal Snellen letter acuity. The test was administered by presenting the entire sequence of plates three times and the Pearson product moment correlations between the scores on the three presentations were

Table 1. Number of errors made on the Cambridge Low Contrast Gratings

Grating number	Total presentations	Total errors	Percent correct	95% confidence limits
1	776	0	100	
2	776	0	100	
3	776	12	98	99–97
4	764	36	95	97–93
5	728	35	95	97–93
6	693	101	85	87–82
7	592	135	77	81–73
8	457	171	63	67–58
9	286	104	64	70–58
10	182	78	57	66–48

The gratings were presented to 97 normal observers according to the recommended procedure (four descending series to each eye). The number of trials on which each grating was presented is tabulated, together with the percentage of those trials on which an error was made, and the 95% confidence limits for that percentage.

greater than 0.78. There was a highly significant effect of age on contrast sensitivity.

The published edition of the Cambridge Gratings was initially sold without norms, an unfortunate necessity because of the revised set of plates. However, since the gratings were printed we have examined 107 normal observers. The observers were selected from hospital employees and patients' relatives. As before, all underwent a routine ophthalmological examination which included Snellen acuity, slit-lamp examination, tonometry and ophthalmoscopy. 10 subjects who were amblyopic in one eye were excluded, leaving 97 observers with normal acuity (5/5 or better) in both eyes. The Cambridge Low Contrast Gratings were administered according to the recommended procedure (four descending series: mean luminance 100 cd m^{-2}) first to the right eye and then to the left. None of the subjects achieved an error-free performance in either eye. Table 1 shows the number of errors on each grating, the number of presentations of that grating, and the percentage of presentations on which a correct score was obtained. It can be seen that, within the confidence limits on the percentage figures, the proportion of correct responses decreases with contrast as might be expected.

Table 2 shows, separately for each age group, the number of subjects, the mean and standard deviation of scores (1) for both eyes, (2) for the poorer eye, and (3) for the difference between scores for the two eyes. The scatterplot shown in Fig. 5 gives details of the relationship between the scores on the two eyes and the difference between the scores.

The above scores are based on the sum of four series in which the gratings were presented in order of decreasing contrast. The table also shows, for comparison, the scores obtained, not from the sum of four series, but from the first series alone. The data tabulated are those for the eye with the poorer score. The Pearson product moment correlation between the score on the first series for the right eye and that from the sum of the four series for that eye was 0.72. The variation between the score on one series and that on the next was such that only 5/97 subjects (6/194 eyes) gave an identical score on each of the four series.

Table 2. Scores on the Cambridge Low Contrast Gratings (published version), shown as a function of the age of the observer. Standard deviations are shown in parentheses after the mean.

Age	Sample size	Total score (mean of two eyes)	Total score (mean for poorer eye)	Difference between total scores on each eye	Mean score on first series (poorer eye)
10–19	13	30.38 (5.47)	27.54 (5.92)	5.69 (4.36)	6.62 (1.50)
20–29	25	35.08 (5.06)	33.76 (5.12)	2.64 (2.33)	8.44 (1.92)
30–39	20	32.90 (3.09)	31.25 (3.10)	3.30 (2.51)	7.10 (1.41)
40–49	13	30.46 (3.79)	28.54 (4.75)	3.85 (3.53)	6.92 (2.02)
50–59	15	28.43 (6.51)	26.60 (5.98)	3.67 (3.22)	6.33 (1.74)
60–80	11	28.59 (3.76)	26.09 (5.18)	5.00 (5.12)	6.64 (1.82)

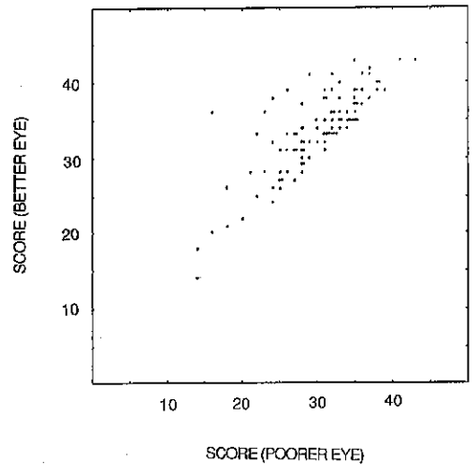

Fig. 5. Scatterplot showing the relationship between scores on the Cambridge Low Contrast Gratings for the stronger and the weaker eyes of normal observers. The difference in the scores on the two eyes (the distance of the points from the diagonal) is not strongly dependent on the absolute value of the scores.

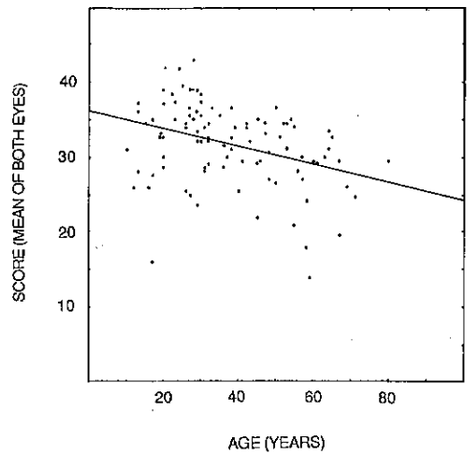

Fig. 6. Scores of normal observers on the Cambridge Low Contrast Gratings, expressed as a function of age. The decrease in sensitivity with age is highly significant: the regression accounts for 12.2% of the variance.

Contrast sensitivity scores decrease with age, as can be seen from the scatterplot in Fig. 6. The Pearson product moment correlation coefficient between age and test scores is 0.35 and the regression accounts for 12.2% of the variance. The regression equation is

$$Y = 36.00 - 0.116\,X \qquad (2)$$

where Y is the mean score for the two eyes and X is the observer's age in years. The slope is significantly different from zero ($t = 3.62$, d.f. $= 95$, $P < 0.0005$). Confidence limits on the slope can be calculated as

$$-0.1159 +/- t*0.0320 \qquad (3)$$

where t has the desired probability value and 95 deg of freedom. Although the maximum scores are obtained in the third rather than the second decade of life, as can be seen from Table 1, the difference between these decades does not reach statistical significance. The decrease in sensitivity with age corresponds to an increase in contrast threshold of about 10% with each decade of life from the teens onwards. The range of sensitivity within the normal population at any given age is about the same as the average deterioration over the life span.

The effects of age on contrast sensitivity have been well documented using cathode ray tube techniques by several previous investigators (Beazley *et al.*, 1980; Hutman and Sekuler, 1980; Sekuler and Hutman, 1980; Sekuler *et al.*, 1980). Therefore, in revealing the age effects, the Cambridge Gratings demonstrate their test sensitivity.

It is hoped to collate normative data from a variety of centres and to publish these data as they become available. Any investigators who examine the contrast sensitivity of normal observers using the Cambridge Gratings are invited to submit their data to the first author, together with details of procedure.

For ease of use in clinical practice Table 3 shows percentile limits of normal performance based on the data in Table 2. Scores less than those shown for the appropriate age group may be considered abnormal.

ERRORS OF OMISSION AND COMMISSION IN CLINICAL PRACTICE

Any clinical examination will miss some

Table 3. Percentile limits of normal performance on the published version of the Cambridge Low Contrast Gratings

Age range	90th percentile	95th percentile	97.5th percentile
10–19	24	22	20
20–29	29	27	26
30–39	29	28	27
40–49	26	25	24
50–59	21	18	16
60–80	24	23	22

Total scores lower than those tabulated may be considered abnormal; i.e. poorer than those expected from 90, 95 and 97.5% of the normal population. (The estimates are based on the data shown in Table 2).

patients who have genuine problems and falsely classify as abnormal other patients who do not. If the examination is adjusted to reduce one type of error the other type will inevitably increase. A compromise between the two types of error has to be reached on the basis of the relative costs of each type. In the present context the analysis of the costs is complex because the consequences of any misclassification of patients depend on the nature of the disease, and there are several very different diseases that can impair contrast sensitivity. Although the early detection of abnormalities in diseases such as glaucoma and diabetes might have considerable prognostic significance, insufficient work has been done to evaluate the role that the assessment of contrast sensitivity might play. It is therefore premature to discuss the clinical power of the Cambridge Gratings. Nevertheless in the studies now to be reviewed a high proportion of patients showed abnormal contrast sensitivity, surprisingly high in view of the fact that few of the patients were complaining of visual symptoms and all had normal Snellen acuity. In general, the correlations betwen contrast sensitivity and the results of other more conventional examinations were low, suggesting that contrast sensitivity can provide a useful ancillary measure. (If the correlations had been large, the additional information gained by measuring contrast sensitivity would have been small, and the only justification for such measurement would have been its simplicity.)

Had the Cambridge Gratings measured several spatial frequencies in addition to 4c/deg, the number of patients with abnormalities would probably have been slightly larger. However, as far as can be judged from published contrast sensitivity functions in patients with ocular and retrobulbar disease, the increase in the number of abnormalities detected would have been small (Regan *et al.*, 1977; Hyvarinen *et al.*, 1983; Ross *et al.*, 1984), although exactly how small remains controversial. Loss of contrast sensitivity can occur as a result of a wide variety of disorders of the retina and of the visual pathways, and, recent claims notwithstanding, the published literature gives little indication that any of these disorders produce a characteristically selective pattern of loss. As previously mentioned, the most common pattern appears to be diffuse loss over all spatial frequencies, but with greatest loss near the peak of the contrast sensitivity function (e.g. Zimmern *et al.*, 1979).

A REVIEW OF CLINICAL STUDIES

The Cambridge Gratings have been used in studies of patients with diabetes, multiple sclerosis, optic neuritis and glaucoma. All the patients who took part were selected as having normal Snellen letter acuity.

Della Sala *et al.* (1984) studied 42 diabetic patients, 20 with type I and 22 with type II diabetes melitus. Fifteen patients had contrast sensitivity scores in the worst eye more than 2 SD below the mean for age-matched controls. There were no differences between the error scores for patients with type I and type II diabetes, or indeed for patients with and without retinopathy. There were, however, substantial differences in the incidence of abnormalities in young and old patients: 14 of the 20 patients aged 10–49 were impaired, as against 2 of the 22 patients aged 50 and above.

In a second study by Della Sala *et al.* (1987), a consecutive series of 10 male and 31 female patients with known or suspected multiple sclerosis were examined. All patients underwent extensive ophthalmological examination, including the visual evoked potential and the Cambridge Gratings. Thirty patients (73%) had contrast sensitivity scores more than 2 SD below a mean for age-matched controls, and 34 (83%) had abnormal VEPs. There was no association between abnormalities of the two types, a finding that is consistent with earlier studies (e.g. Kupersmith *et al.*, 1983). Patients who had impaired contrast sensitivity and normal VEPs were younger than those whose contrast sensitivity was normal but whose VEPs were not. In Table 4 all the patients in the lower left cell were aged 35 or less; all those in the upper right were 35 or more. As with diabetic patients, the Cambridge Gratings were more sensitive at revealing visual deficits in the young than in the old.

Table 4. The incidence of abnormalities of contrast sensitivity (CS) and of the visual evoked potential (VEP) in a sample of patients with multiple sclerosis (from Della Sala *et al.*, 1987)

		VEP	
		Normal	Abnormal
CS	Normal	2	9[b]
	Abnormal	5[a]	25
			41

[a]All aged 35 or less.
[b]All aged 35 or more.

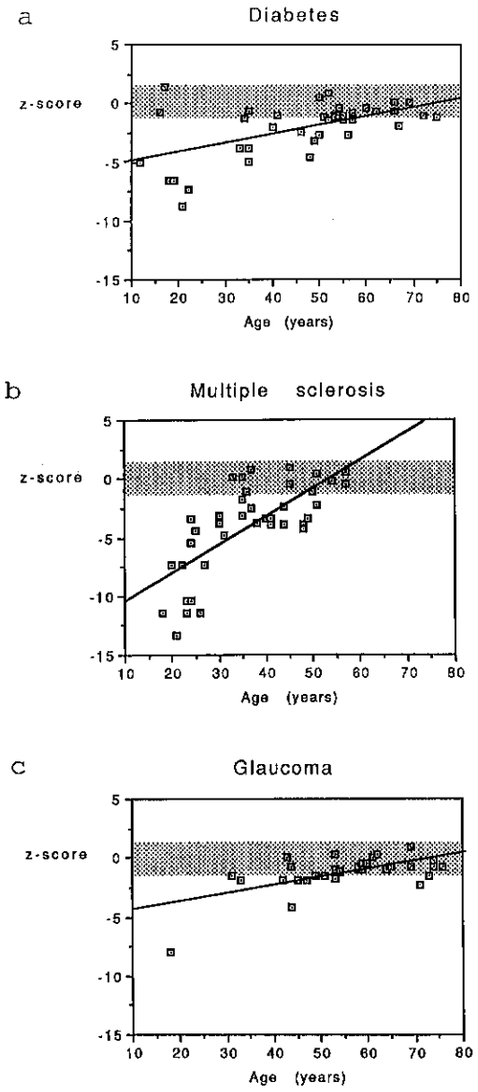

Fig. 7. Scores on the Cambridge Low Contrast Plates in patients with diabetes, multiple sclerosis and glaucoma. The scores have been expressed as z-scores (number of standard deviations from the mean for normal controls of similar age). Each z-score is shown as a function of the patient's age. The shaded area indicates the normal range (10–90th percentile); thus points below the shading represent patients with abnormally poor scores. The oblique lines show the regression of z-scores with age, significant in each case ($R = 0.57$, 0.73 and 0.60 respectively), indicating that abnormalities are more common in the young.

In the above series of patients with multiple sclerosis, nine had a well-documented history of optic neuritis. Contrast sensitivity was the only examination to reveal deficits in all nine patients.

Somazzi *et al.* (1988) have examined a consecutive series of 37 patients with a history of raised intraocular pressure, 29 of whom were affected by primary bilateral chronic open-angle glaucoma. Scores on the Cambridge Gratings were below the 10th percentile for age-matched controls in 14 of the patients with glaucoma and three of the eight in whom ocular hypertension was the only sign. The association between abnormalities in contrast sensitivity and visual fields was weak (accounting for 18% of the variance) and there was no significant association between contrast sensitivity and the intraocular pressure at the time of examination. As in the case of diabetes and multiple sclerosis, the incidence of abnormal contrast sensitivity was higher in the young. Figure 7 summarises the data from the three studies, showing the z-scores as a function of age. The z-scores were obtained by comparing patient's raw scores on the poorer eye with the corresponding scores for normal controls of similar age. No regression as a function of age is therefore to be expected. Nevertheless the regression with age is significant in all three studies. Although it is possible that this regression is due to ceiling effects amongst controls tested on the original version of the gratings, an alternative explanation is that, with advancing age, people are increasingly subject to a variety of disorders, many of which may reduce contrast sensitivity. As a result, contrast sensitivity loss due to any particular disorder may have to be large before it falls outside the limits of normal performance. On the basis of such an explanation one might expect an increase with age in the variance of contrast sensitivity within the normal population. The scattergram shown in Fig. 6 gives no indication of such an increase, perhaps because participants were ophthalmologically screened.

Figure 7 shows that multiple sclerosis and diabetes tend to be associated with a higher incidence of contrast sensitivity loss than glaucoma; possibly because patients with glaucoma tend to be older, and because the associated impairment may selectively involve the periphery of the visual field.

In describing the above studies the findings for scores on the worst eye have been quoted. If scores for the two eyes are combined a very similar pattern of deficits emerges in all studies except those involving optic neuritis. In seven of the nine patients with optic neuritis the neuritis was bilateral, and in three of these seven the contrast sensitivity was impaired only in the affected eye.

The above studies used the first version of the

Gratings. The published version has also been used but so far only in two completed studies. One was an investigation of the visual effects of the travel sickness drug, scopolamine. A dose-dependent reduction in contrast sensitivity was obtained at low doses that had no effect on Snellen acuity, grating acuity or pupil diameter (G. C. Preston, personal communication). The mean (and standard deviation) for scores in the placebo condition was 35.13 (6.57) for 15 observers aged 20–29 and 36.87 (3.60) for 15 aged 30–39. These scores compare reasonably well with those in Table 2. In the second study patients with seasonal affective disorder were found to have abnormal contrast sensitivity (CD Binnie, personal communication).

CONCLUSION

The Cambridge Low Contrast Gratings provide a simple, rapid, inexpensive but reliable measure of contrast sensitivity. The test commonly reveals deficits in patients with diabetes, multiple sclerosis, optic neuritis and glaucoma who have normal Snellen letter acuity, and who fail to show deficits on more conventional ophthalmic tests. The value of contrast sensitivity in routine screening has yet to be assessed, but it is likely to be greater in the young than in the elderly.

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