COLOUR CONTRAST THRESHOLDS ARE NORMAL IN FUNCTIONAL AMBLYOPIA

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SUMMARY

We evaluated colour contrast thresholds in patients with unilateral functional amblyopia. A computer-controlled colour vision test was used to determine colour contrast thresholds along a blue–yellow tritan axis. Prior to the threshold measurement, a heterochromatic flicker brightness test was performed to ensure isoluminance between the test stimulus and the background for every subject individually. Luminance contrast thresholds were also measured using the same computer-based system. Twenty amblyopic patients were tested. All showed normal tritan colour contrast thresholds both for their amblyopic eye and non-amblyopic fellow eye. Luminance contrast thresholds were elevated in all 6 refractive amblyopic eyes, in 4 of 9 strabismic eyes and in 2 of 5 mixed amblyopic eyes. Colour contrast thresholds are normal in functional amblyopia (with central fixation). Whenever elevated tritan colour contrast thresholds are found in patients with a decreased visual acuity, other causes of visual impairment are to be evaluated.

Various reports document the incidence of amblyopia at 1–4% of the general population.[1,2] When a patient presents to the ophthalmological clinic with a unilateral decrease in visual acuity, there is not always a positive history allowing the loss of visual acuity to be attributed to amblyopia. An important clinical sign for differentiating between functional amblyopia and several acquired pathologies that also present with diminished visual acuity is the colour vision of the patient. Some of the acquired pathologies, such as optic neuropathies, show a distinctive change in colour vision.[3] The colour sense in eyes with functional amblyopia depends on the mode of fixation.[3] With foveolar fixation the standard colour tests give normal results, but specialised examination methods can detect depressions in retinal sensitivity and slight reductions in wavelength discrimination ability.[4–6] With increasing eccentricity of fixation, colour vision increasingly deteriorates.[3]

Our study was set up to evaluate whether colour contrast thresholds measured with a computer-controlled colour vision test are altered in functional amblyopia. Recently this new and very sensitive computer-based colour vision test has been introduced in clinical colour vision testing. Colour contrast thresholds are determined using a PC system with a high-quality TV monitor as described by Arden *et al.*[7,8] A test stimulus is displayed on a background with the same luminance (to ensure the background does not provide any luminance clues to detecting the stimulus). Hence the image can only be recognised by a difference in colour between stimulus and background. The colour contrast threshold is defined as the smallest colour difference between stimulus and background that can be discriminated by the subject. To ensure isoluminance between the test stimulus and background, each subject has to perform a heterochromatic flicker brightness match. This system not only enables sensitive and rapid testing of colour vision, but it also offers a quantitative approach.

We decided to restrict our study to measuring colour contrast thresholds along a single blue–yellow tritan axis for two reasons. Firstly, the blue–yellow axis is highly suitable for detecting acquired colour vision defects even in the presence of a previously unknown congenital red–green defect.[9] Secondly, confining the test to the tritan axis enabled us to shorten the test time, which helped our young patients to maintain their concentration. Since luminance contrast sensitivity functions in amblyopic patients are disturbed, as extensively described in the literature,[2,10-14] we wanted to compare the colour contrast thresholds along the tritan axis with the luminance contrast threshold measured with a similar

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stimulus chosen from a range of grey tones. Hence the task for all our amblyopic and normal control subjects was threefold for each eye: they had to perform a luminance contrast threshold measurement, a heterochromatic flicker brightness match and a colour contrast threshold determination.

PATIENTS AND METHODS

Heterochromatic flicker brightness matching and colour and luminance contrast threshold measurements were performed using a system previously described in detail by Arden *et al.*[7,8] A personal computer (Compaq Deskpro 386S, 16 MHz) displays the image on a high-quality TV monitor (NEC). The display board used is a TSL 206 with a 24-bit palette, operating at 100 MHz on a 980 × 768 pixel display with a 94 Hz refresh rate.

The heterochromatic flicker brightness test uses a red and a green square alternating at 22 Hz. The subject has to use 'mouse' buttons to adjust the radiance of the green square so that flicker sensation is minimal. Then the same adjustment is performed for a blue and a green square. The software program uses the red/green radiance ratio (R/G ratio) and the blue/green radiance ratio (B/G ratio) to calculate the isoluminant test colours for each subject individually.

To determine the colour contrast threshold, a capital letter is presented on an isoluminant background. The computer makes a random choice of one letter out of a possible ten. For children of preschool age one of five capital letters, comparable to the Stycar V test for visual acuity, appears. The capital letter subtends 3.3° vertically, 3.6° horizontally; the width of the components was 0.6° at the viewing distance of 1.5 m. An appearance–disappearance mode at 1 Hz was used with a duty cycle of 20%. Threshold determinations were carried out using a modified binary search method. The colour contrast threshold (expressed as a percentage) is defined as the smallest colour difference between the stimulus and the background that could be discriminated by the subject. The colour contrast threshold is 0 when letters and background have the same colour and 100% when the difference between colours is the maximum possible with the system.

Luminance contrast threshold was determined using the same technique (i.e. a capital letter, a modified binary search method etc.). The monitor provided a background field with a mean luminance of 30 cd/m^2 and x,y chromaticity coordinates of 0.333 and 0.333. The maximum luminance of the letter was 35.5 cd/m^2. The luminance contrast is calculated using the formula:

$$\text{Contrast} = \frac{\text{Luminance of the background} - \text{Luminance of the test stimulus}}{\text{Luminance of the background} + \text{Luminance of the test stimulus}}$$

This gave a maximal contrast of 8%.

All threshold determinations and heterochromatic flicker brightness matching were carried out monocularly. Where necessary subjects wore the appropriate refractive correction.

Patient Selection

Twenty patients with unilateral functional amblyopia were selected in our orthoptic department. A full ophthalmological examination with slit lamp evaluation and ophthalmoscopy with dilated pupils was performed to exclude any organic pathology: all patients had to have clear ocular media (no corneal opacities, clear lens, clear anterior and posterior chamber) and a normal fundoscopic appearance of the macula, optic disc and retinal periphery. Only patients capable of reading a Stycar V or Snellen chart were admitted to the study. The minimum allowable Snellen visual acuity of the amblyopic eye was 6/60 (0.1). All patients underwent a full orthoptic examination, which included a cover test and alternate cover test in primary position, on near and distance fixation. Retinoscopy and indirect fundoscopy were carried out under full cycloplegia and fixation behaviour was determined with the visuscope.

Twenty patients matched our inclusion criteria. They were divided into three groups according to the cause of their amblyopia: (1) anisometropic amblyopia (1 dioptre (D) difference in spherical equivalent between the two eyes) ($n = 6$), (2) strabismic amblyopia ($n = 9$), (3) mixed amblyopia ($n = 5$). In the last group, it was unclear whether the squint or the refractive error had induced the amblyopia primarily. The age of the amblyopic patients ranged from 5 to 46 years (with a median age of 7 years) and the visual acuity of the amblyopic eyes ranged from a Snellen acuity of 6/60 (0.1) to 6/9 (0.7) (median 6/15 (0.4)). None of the strabismic patients showed eccentric fixation.

Normal values for each test were obtained from a control group of 24 subjects with an age ranging from

Table I. Tritan colour contrast thresholds (expressed as percentages) of the normal subjects and of the amblyopic eyes and their non-amblyopic fellow eyes

	Normal subjects ($n = 24$)	Amblyopic eyes ($n = 20$)	Non-amblyopic fellow eyes ($n = 20$)
Mean	9.1	10.1	9.7
Minimum–maximum	5.5–15.3	5.0–14.9	5.9–15.1
Standard deviation	2.9	2.9	2.7

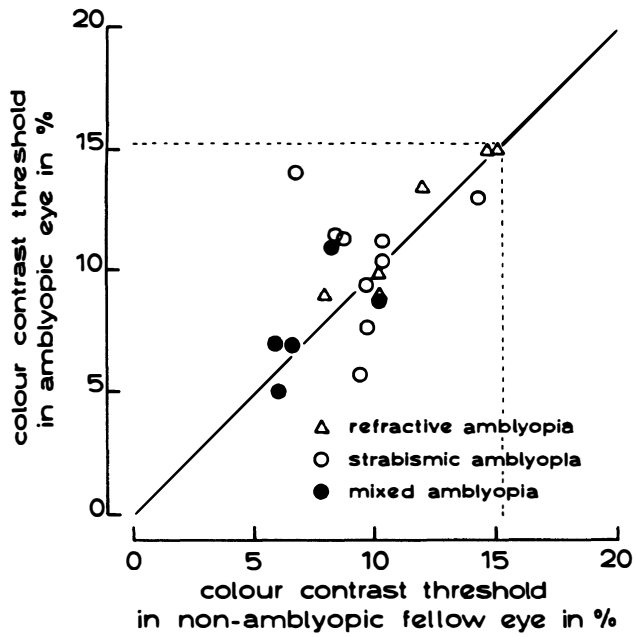

Fig. 1. *Scatter diagram of the colour contrast thresholds (expressed as percentages) along the tritan axis for the amblyopic and the non-amblyopic fellow eyes of the patients. The dashed lines signify the upper limits of normal. The straight line is the bisectrice of the diagram.*

5 to 47 years (mean age 22 years), of whom only one eye was examined.

RESULTS

Tritan Colour Contrast Thresholds (Table I)

We measured the colour contrast thresholds along the tritan axis in one eye of 24 normal subjects and in both eyes of 20 patients with unilateral amblyopia, after each subject had performed a heterochromatic flicker brightness match monocularly. The mean colour contrast threshold along the tritan axis for the normal subjects was 9.1% (minimum 5.5%, maximum 15.3%, standard deviation (SD) 2.9%). The 20 amblyopic eyes presented with a mean threshold of 10.1% (minimum 5%, maximum 14.9%) and a SD of 2.9%. The 20 dominant fellow eyes of the patients reached a mean threshold value of 9.7% with a minimum of 5.9% and a maximum of 15.1%. The SD was 2.7%. A statistical analysis with a two-tailed *t*-test for independent samples showed no statistically significant difference between the eyes of the normal subjects and the amblyopic eyes ($p>0.1$) and between the eyes of the normal subjects and the dominant fellow eyes of the patients ($p>0.1$). A *t*-test analysis for paired samples revealed no statistically significant difference between the amblyopic and non-amblyopic fellow eyes either ($p>0.1$). The values of the tritan colour contrast thresholds for the amblyopic eyes and the non-amblyopic fellow eyes of the patients are shown in Fig. 1. We divided the amblyopic patients into three groups according to the classification in the patient selection: 6 patients with anisometropic amblyopia, 9 with strabismic amblyopia and 5 with mixed amblyopia. The upper limit of normal was a contrast threshold of 15.3%. All threshold values of both the amblyopic eyes and the non-amblyopic fellow eyes for the anisometropic, strabismic and mixed amblyopic patients fell within this limit. We found a correlation between the colour contrast thresholds of the amblyopic eyes and their non-amblyopic fellow eyes ($r = 0.66$). Fig. 2 displays the tritan colour contrast thresholds of the 20 amblyopic eyes as a function of their visual acuity.

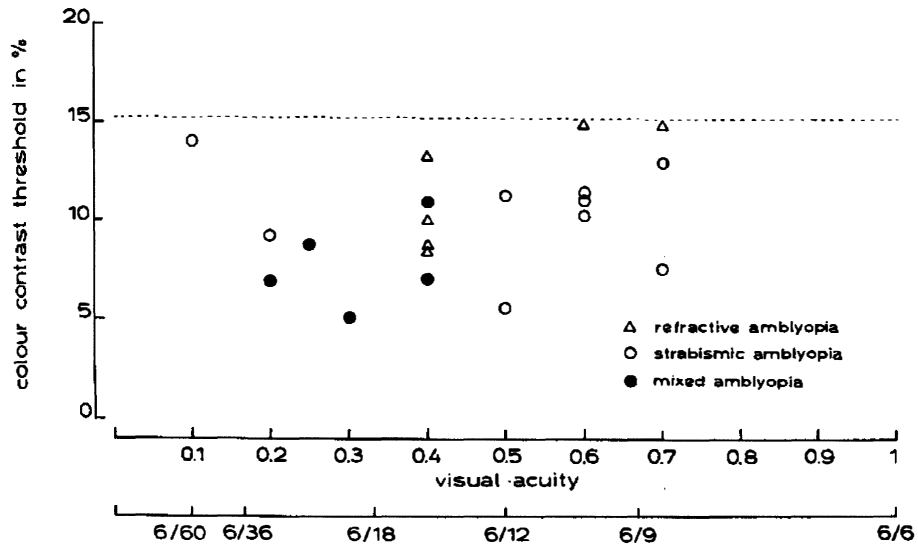

Fig. 2. *Snellen visual acuity versus the colour contrast thresholds (expressed as percentages) along the tritan axis for the amblyopic eyes.*

Table II. Heterochromatic flicker brightness R/G and B/G ratios of the normal subjects and of the amblyopic eyes and their non-amblyopic fellow eyes

	Normal subjects (n = 24)	Amblyopic eyes (n = 19)	Non-amblyopic fellow eyes (n = 19)
(a) *R/G ratios*			
Mean	0.97	0.91	0.95
Minimum–maximum	0.20–1.22	0.75–1.11	0.75–1.10
Standard deviation	0.12	0.12	0.12
(b) *B/G ratios*			
Mean	0.74	0.70	0.74
Minimum–maximum	0.42–1.10	0.55–0.94	0.57–0.96
Standard deviation	0.15	0.11	0.13

No correlation between the visual acuity ranging from Snellen acuity 6/60 (0.1) to 6/9 (0.7) and the tritan colour contrast thresholds was found ($r = 0.3$).

Heterochromatic Flicker Brightness Match

Twenty-four normal subjects and 20 amblyopic patients performed a heterochromatic flicker brightness match. The R/G and the B/G ratios were analysed.

The *R/G ratios* (Table IIa) of the normal subjects showed a normal distribution. The values of the amblyopic and non-amblyopic eyes also displayed a normal distribution except for 1 clearly different patient with a high R/G ratio. This patient was known to have a congenital red–green colour defect. Note that this patient showed a normal tritan colour contrast threshold.[9] The values of the mean, minimum and maximum ratios as well as the SD are shown in Table IIa. No statistically significant difference was found between the R/G ratios of the eyes of the normal subjects and the amblyopic eyes (t-test for independent samples, $p>0.1$) or the dominant fellow eyes ($p>0.01$). A paired t-test analysis did not find any statistically significant difference between the amblyopic eyes and their fellow dominant eyes ($p>0.05$).

The *B/G ratios* (Table IIb) of the normal subjects and the patients showed a normal distribution. The 1 patient with high R/G ratios also had the lowest B/G ratios. The mean B/G ratios with minimum, maximum and standard deviation for the eyes of the normal subjects, the amblyopic eyes and the dominant fellow eyes are shown in Table IIb. No statistically significant difference was found between the normal subjects and the patient group ($p>0.1$ for the normal subjects vs amblyopic eyes, and $p>0.1$ for the normal subjects vs non-amblyopic fellow eyes). A statistically significant difference was found between the 20 amblyopic eyes and their fellow dominant eyes ($0.05>p>0.01$).

Luminance Contrast (Table III)

The luminance contrast threshold was investigated in one eye of 24 normal subjects and in both eyes of the 20 patients with unilateral amblyopia.

The mean luminance contrast threshold of the eyes of the normal subjects was 0.8% (minimum 0.6%, maximum 1.0%, SD 0.1%). We found slightly increased luminance contrast thresholds in the amblyopic eyes for all 6 refractive, 4 of the 9 strabismic and 2 of the 5 mixed amblyopic patients. In the fellow eyes the thresholds were slightly elevated in 5 of the refractive, in 2 of the strabismic and in 1 of the mixed amblyopic patients. The maximum observed contrast thresholds for the amblyopic eyes and their fellow eyes were 2.0% and 1.6% respectively.

DISCUSSION

We investigated the colour contrast threshold along the tritan axis in both eyes of 20 amblyopic patients. We found normal thresholds for both the amblyopic and the non-amblyopic eyes. Note that care was taken that all patients showed a central fixation pattern. In the 1960s and 1970s much work was done in investigating the colour vision of amblyopic patients (Roth[16] and Pokorny *et al.*[3] give excellent reviews). Colour vision in eyes with functional amblyopia is dependent on the mode of fixation. With foveolar fixation the standard clinical tests give near-normal results.[3] Roth[16] found in 6 of 19 subjects with amblyopia and foveolar fixation a difference in the readings of the pseudoisochromatic AO-HRR plates between the amblyopic eye and the fellow

Table III. Luminance contrast thresholds (expressed as percentages) of the normal subjects and of the amblyopic eyes and their non-amblyopic fellow eyes

	Normal subjects (n = 24)	Amblyopic eyes (n = 20)	Non-amblyopic fellow eyes (n = 20)
Mean	0.8	1.2	1.0
Minimum–maximum	0.6–1.0	0.7–2.0	0.6–1.6
Standard deviation	0.1	0.5	0.3

dominant eye, although these differences did not fall outside the normal limits. On the Farnsworth Panel D-15 test, amblyopic patients with foveolar fixation showed normal results.[3,16,17] According to Roth,[16] on the Farnsworth Munsell (FM) 100-hue test amblyopic observers with foveolar fixation had error scores within the limits of the normal population, but often the numbers of errors for the amblyopic eyes were higher than for the corresponding dominant eyes. Frühauf *et al.*[18] even found significantly higher error scores in the dominant eyes of strabismic patients. Usually the FM 100-hue test errors for amblyopic eyes with foveolar fixation show no predominant axis,[3,18] but Roth[16] reported some predominance of a type III bipolar blue–yellow axis. More specialised examination of amblyopic eyes with, for example, wavelength discrimination curves by Marré and Marré[5,6] showed that amblyopic eyes with foveolar fixation had hue discrimination that could be normal, slightly reduced in the short-wave range or slightly impaired over the whole spectrum. With increasing eccentricity of fixation, colour vision undergoes increasing deterioration.[3,4,5,6,16–18]

Most tests in clinical use, such as the Ishihara pseudoisochromatic plates, the Panel D-15 and the FM 100-hue, are not designed to detect acquired colour deficiencies. Only the FM 100-hue test can not only detect congenital defects in colour vision but also evaluate chromatic discrimination loss in acquired pathologies. Furthermore this test is not merely qualitative, but also quantitative. The FM 100-hue test has, however, a number of inherent shortcomings: the hues used are not truly isoluminant for the test subjects, tints may vary with age and use, the illumination may not be standard, and the subject may have a spectral sensitivity curve that differs from the average. Thus the subject may arrange the caps not only by hue but also by luminance. The FM 100-hue test is also time-consuming and elaborate. The computer-based colour vision test system used has a number of advantages over other colour vision tests: it establishes each subject's isoluminance values at the beginning of each test, it offers a quantitative approach and it reaches a threshold very rapidly. The increments in hue separation which are available are fine by comparison with the 85 discs in the FM 100-hue test. Previous studies have shown that this computer test can detect changes in colour vision where the other tests may fail.[8,19]

Our much more sensitive test could not, however, confirm the presence of minor alterations in the colour sense of amblyopic eyes with foveolar fixation. The findings of normal colour contrast thresholds provide us with a sensitive, easy, quick and quantitative method of differentiating between functional amblyopia and other causes of visual impairment presenting with a change in colour vision. As in the other colour vision tests, the determination of the tritan colour contrast threshold is a subjective test in which active cooperation of the patient is needed. Some of the pre-school children had difficulty performing the flicker brightness test, in particular those not used to video and computer games. They had to be guided carefully to achieve satisfactory and reliable flicker brightness values. Three additional patients could not perform a satisfactory heterochromatic flicker brightness test themselves. The nurse, known to have normal heterochromatic flicker brightness values, performed their flicker brightness test. As a consequence the calculated colours could possibly be somewhat different from the individually isoluminant colours and image recognition may in part have been due to luminance clues; therefore they were not included in the results described above. Note, though, that their tritan colour contrast thresholds fell within normal limits.

Luminance contrast thresholds were slightly elevated in 12 amblyopic and 8 non-amblyopic eyes. Luminance contrast sensitivity measured with sinusoidal gratings has been reported to be defective for the high spatial frequencies also, in both the amblyopic eye and non-amblyopic fellow eye.[2,10–14] Although our methods used to obtain luminance contrast thresholds are completely different, our results were in the expected range of values.

In conclusion, we can state that colour contrast thresholds along the tritan axis measured with a computer-controlled colour vision test are normal in functional amblyopic patients with central fixation. Whenever a patient presents in clinic with unilateral depressed visual acuity and an uncertain history of amblyopia, the tritan colour contrast threshold can rapidly differentiate between functional amblyopia and any superimposed organic factors.

Key words: Amblyopia, Colour contrast threshold, Luminance contrast threshold, Heterochromatic flicker brightness match, Colour vision, Acquired colour deficiencies.

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