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ANOMALIES IN THE APPEARANCE OF COLOURS AND OF HUE DISCRIMINATION IN OPTIC NEURITIS

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Summary—1. The experiments described aim to quantify the changes in the appearance of colours in optic neuritis by measuring the changes in hue, chroma (saturation) and value (lightness) in the affected eye. In addition we tested whether deficits in hue discrimination can be solely accounted for by losses in perceived saturation or lightness.

2. Stimuli were Munsell chips taken from the Munsell Book of Color. An interocular matching technique was used to measure colour appearance. A modified version of the Farnsworth–Munsell 100-hue test was used to investigate hue discrimination.

3. Results show that the predominant deficit is a loss of chroma (saturation) which can occur at any hue. Changes in hue can also occur. These are not confined to any particular hue and occur such that hues tend to shift in appearance towards one of the four unique hues. Deficits in the discrimination were found which were not accounted for by losses in chroma or value.

4. Overall, the results indicate that in the case of optic neuritis there were notable exceptions to Köllner's rule and the Verriest and Wald–Marré classifications of optic nerve disorders.

Key words—Optic neuritis; colour appearance; hue discrimination; acquired colour vision deficiencies.

INTRODUCTION

Optic neuritis is defined clinically as an episode of visual failure which is of rapid but not sudden onset, followed by recovery, and for which no toxic, vascular or other cause is found. Whilst the aetiology is unknown, and there may be more than one cause, most cases are thought to be due to multiple sclerosis (MS). A permanent residual visual deficit is common but rarely severe. The visual field is always affected patchily and there is no evidence that any particular region of the visual field, such as that subserved by the foveal projection, is more likely to be affected (Perkin and Rose, 1979; Plant and Hess, 1987).

In recent years there has been much research into the nature of the visual deficits which result from an attack of optic neuritis. Attention has been directed towards an analysis of the disordered colour vision in optic neuritis since subjective reports of alterations in the appearance of colours are very common (see MacKarell, 1986 for a pictorial account of symptoms and Foster, 1986 for a review of disordered colour vision in optic neuritis). Clinicians have been aware that the desaturated appearance of colours and abnormalities of hue discrimination are sensitive indicators of optic nerve disease including optic neuritis (Gunn and Buzzard, 1897; Sloan, 1942; Glaser, 1976; Griffen and Wray, 1978). In the clinical literature it has been implied that colour vision may be more affected than achromatic sensitivity (for example in the demonstration of visual field defects, Gunn and Buzzard, 1897) and that red-green deficiencies may be more common than blue-yellow deficiencies (Nagel, 1907; Marré 1973; Chisholm, 1979). Köllner (1912) stated that red-green defects are characteristic of optic nerve disorders including optic neuritis, a view which continues to receive support (see Pokorny and Smith, 1986 for a recent review) and which has been referred to as a Type II deficit in Verriest's classification of acquired colour vision disorders (Verriest, 1963).

The experiments described in this paper have been designed to quantify more completely the alterations in the appearance of surface colours

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in optic neuritis. An interocular matching technique has been devised to show how the appearance of colours alters for the complete colour circle. It has been possible to investigate whether the desaturated appearance varies with hue and whether any particular hues are more likely to be affected. Secondly we have been able to determine whether the anomalous colour naming is entirely a consequence of alterations in saturation or in brightness, or whether genuine shifts in perceived hue occur. Hue discrimination has been studied using the Farnsworth–Munsell 100 hue test to determine whether impaired discrimination is specific for any region of the colour circle. In addition the information obtained in the interocular matching experiment has been used to investigate whether the impaired hue discrimination can to any extent be accounted for by the loss in perceived saturation and the variations in that loss with hue.

It is likely that the residual deficit in optic neuritis results principally from the effects of demyelination or axonal degeneration or both within the optic nerve. It is possible, however, that in *acute* phase of the disorder oedema of the optic nerve may contribute to the deficit. Furthermore, lesions at other locations in the visual pathways may be present: there is evidence for a retinal abnormality in MS and optic neuritis (McDonald, 1986; Plant *et al.* 1986; Plant and Hess, 1986) and even in cases of "isolated" optic neuritis lesions are often present elsewhere in the white matter with a possible predeliction for the occipital lobes (Ormerod *et al.*, 1986). In the present study we have looked only at the chronic residual deficit and have compared the visual deficit between the two eyes of each subject, thus controlling for any post-chiasmal pathology, which is likely to affect both eyes.

METHODS

Colour appearance was measured using the Munsell notation and all stimuli used in the experiments were rectangular coloured chips from the Munsell Book of Color (Glossy collection, 1976). The Munsell book, illustrated in Fig. 1, is a colour atlas which represents colour appearance using three principal axes. These axes, specifying the perceptual colour solid, are hue (angle about a central, neutral axis) chroma or saturation (distance from the central axis) and value or lightness (distance up the central axis). Each page of the Munsell book holds a selection of removable coloured chips. Along any row, chips vary in chroma but are of uniform value. All the steps in chroma are intended to be perceptually equal. Along any column, chips increase in value from dark at the bottom of the page to light at the top, but are of uniform chroma. All steps in value are intended to be perceptually equal, although different in magnitude from the steps in chroma. The chips on each page are of constant hue, and page by page hue varies to form a colour circle. Hue is represented by 10 principal hues (R, YR, Y, GY, G, BG, B, PB, P, RP) which are each subdivided into four hue steps (2.5 R, 5 R, 7.5 R, 10 R etc) and each step is represented on one page in the Munsell book (a total of 40 pages). The 40 hues are intended to be equispaced. As chroma is reduced the colour space is constricted and visible differences between hues are reduced.

In this colour solid, constant value (isolightness) planes are a series of stacked horizontal surfaces, whereas constant chroma (isosaturation) planes are a series of concentric cylinders expanding out from low to high chroma (see Wyszecki and Stiles, 1967, 476–478 for an illustration). These planes are limited and broken by the boundaries of the colour solid, although in practice the representation of the outer surfaces of the solid in the Munsell book are limited by the manufacturing process. At both higher and lower values the number of perceptual steps in chroma is reduced (Boring, 1937; Newhall *et al.*, 1943) and so only a limited number of chroma samples are available in the book at these values.*

In the experiments, the subject's good eye was

*The Munsell system of representing colour appearance was first devised by Munsell (Munsell, 1905) and was later extensively revised (Newhall, 1940; Newhall *et al.*, 1943). The method relies on an extensive series of judgements of perceptual differences along the three axes made by 41 observers coupled with smoothing of the results on CIE coordinates (Newhall, 1939, 1940). While the ideal colour solid would be calibrated in perceptually uniform steps, the achievement of this in practice is a complex task (Newhall, 1939; Boring, 1939). In particular, some non-uniformity of the chroma scales is apparent at the lowest value of 2 in the book. The particular difficulty of judging chroma at low values has been previously reported (Newhall, 1939, 1940). These non-uniformities will not affect the results reported here since values below 3 were not used. Details of the relationship between the Munsell colour representation and the CIE chromaticity diagram can be found in Wyszecki and Stiles, 1967, pp. 479–500 and Newhall *et al.*, 1943.

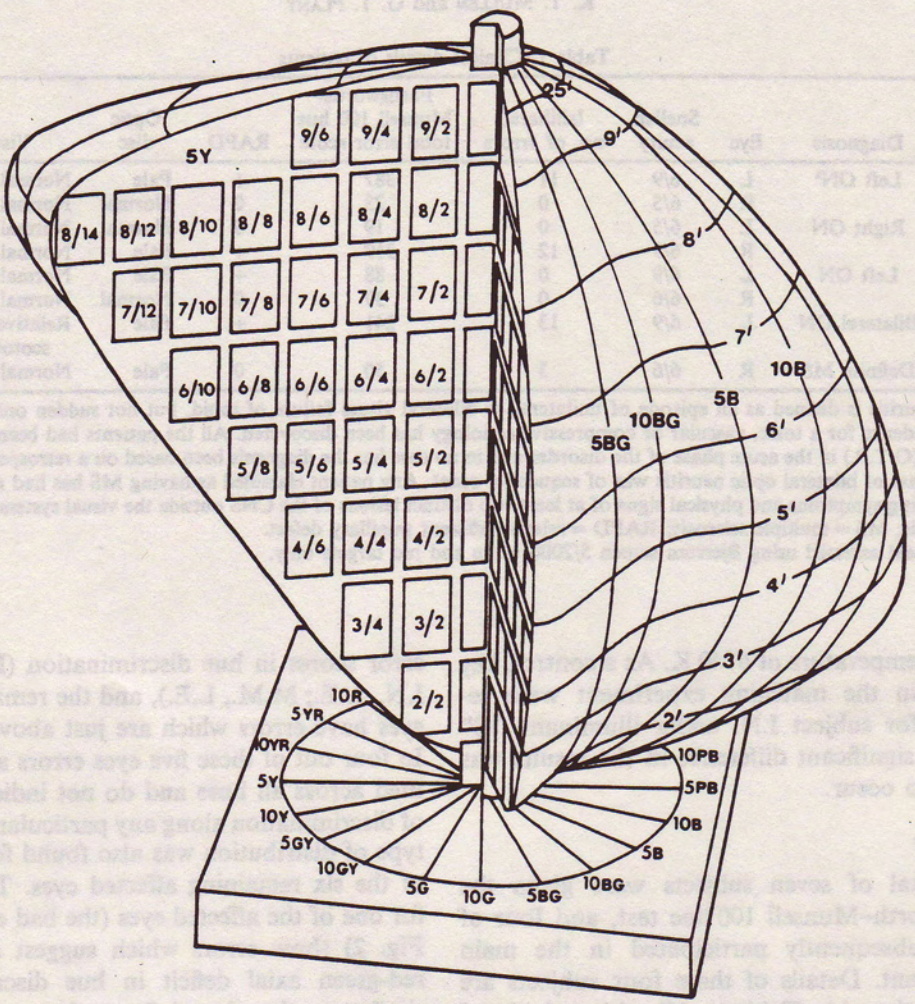

Fig. 1. Diagram of the Munsell Book of Color, a colour atlas of 40 pages. Each page contains arrays of removable coloured chips. The chips on each page are of constant hue and page by page hue varies. Along each row, chips vary in chroma (saturation) and along each column they vary in value (lightness). Further details are given in the text.

used to match colours viewed with the bad eye, by using a between-eye matching paradigm. Both test and matching chips were viewed on a uniformly illuminated white background under overhead fluorescent room illumination of colour temperature 7000 K and with an illuminance upon the colour chips of 480 lx. The mean luminance of the white background was 230 cd/m^2, and the mean luminance of the test chips was around 140 cd/m^2 although the exact value depends on the lightness of the test chip used. The chips subtended 3 × 2.4 deg viewed at 40 cm.

A central screen was arranged to obtain dichoptic viewing conditions. The subjects viewed the test chips with their worse eye and used their good eye to select a matching chip from the Munsell Book. Chips selected by the subject were drawn from the book by the experimenter and placed on the white background, so both test and matching chips were viewed under identical conditions before a final match was made. The majority of matches were made two or three times and plotted data points show the averaged results. Whenever possible, standard deviations were calculated and typical values are given in the legends of Fig. 4. Matches made in different sessions were found to be very repeatable. A control study on normal subjects using this experimental paradigm established that very small errors in interocular matching are made by normal subjects. These were not greater than one unit in croma, value or hue, and errors in matching value were rare. Although the room illumination was not by illuminant "C", it was close to the recommended

Table 1. Clinical details of patients

Case	Diagnosis	Eye	Snellen acuity	Ishihara, no. of errors	Farnsworth–Munsell 100 hue total error score	RAPD	Optic disc	Visual field[b]
I.N.	Left ON[a]	L	6/9	11	387	+	Pale	Normal
		R	6/5	0	23	0	Normal	Normal
P.S.	Right ON	L	6/5	0	19	0	Normal	Normal
		R	6/9	12	319	+	Pale	Normal
C.S.	Left ON	L	6/9	0	88	+	Pale	Normal
		R	6/6	0	39	0	Normal	Normal
M.M.	Bilateral ON	L	6/9	13	241	+	Pale	Relative paracentral scotoma
	Definite MS	R	6/6	3	50	0	Pale	Normal

[a]Optic neuritis is defined as an episode of unilateral or bilateral visual failure of rapid, but not sudden onset for which no evidence for a toxic, vascular or compressive aetiology has been discovered. All the patients had been seen by one of us (G.T.P.) in the acute phase of the disorder and in no case has the diagnosis been based on a retrospective history. The case of bilateral optic neuritis was of sequential onset. Any patient classified as having MS has had remitting and relapsing symptoms and physical signs of at least two distinct lesions of the CNS outside the visual system. ON = optic neuritis; MS = multiple sclerosis; RAPD = relative afferent pupillary defect.

[b]Visual field assessed using Bjerrum screen 5/2000 white and red targets only.

colour temperature of 6740 K. As a control, key results in the matching experiment were repeated for subject I.N. under illuminant "C" and no significant difference in the results was found to occur.

Subjects

A total of seven subjects were given the Farnsworth–Munsell 100 hue test, and four of these subsequently participated in the main experiment. Details of these four subjects are given in the table (Table 1). All subjects had had an episode of optic neuritis in the recent past which had left them with a stable residual deficit. Three of these subjects (with the exception of C.S.) show marked interocular differences in their performances on the Ishihara tests for colour deficiencies and the Farnsworth–Munsell 100 hue test. Each subject has one "good" eye which is nearly or completely unaffected by the disease (see results for further details).

RESULTS

The Farnsworth–Munsell 100 hue test

The Farnsworth–Munsell 100 hue test was given to 7 subjects with recovered or chronic optic neuritis, who had 11 affected eyes between them. The results for both eyes of the four subjects who subsequently participated in the experiment are given in Figs 2 and 3, and show the averaged results of two tests for each eye. The results show that three out of the five eyes affected by the condition have abnormally high error scores in hue discrimination (P.S., R.E.; I.N., L.E.; M.M., L.E.), and the remaining two eyes have errors which are just above average. In four out of these five eyes errors are distributed across all hues and do not indicate a loss of discrimination along any particular axis. This type of distribution was also found for five out of the six remaining affected eyes. The results for one of the affected eyes (the bad eye of I.N. Fig. 2) show errors which suggest a possible red-green axial deficit in hue discrimination similar to that found for a deuteranopic observer since errors are greatest at Y to YR and around PB.

Overall, the data of Table 1 and of Figs 2 and 3 show that the subjects represent varying degrees of severity of the disease. These subjects have marked differences in severity between their good and bad eyes, with the exception of C.S. The good eyes of the subjects perform normally with the possible exception of M.M. who is the only subject of the four known to have bilateral optic neuritis (of sequential onset) and whose good eye is slightly affected.

Representation of the Munsell color space

The results of the colour matching experiments in the four subjects are given in Figs 4, 5, 6 and 7. The results for hue and chroma are plotted in polar co-ordinates on a colour "wheel", shown in the upper panel of each figure. The centre of the wheel represents a neutral colour (a shade of grey) and chroma at constant hue varies along the radii from 2 (the inner circle) to 14 (the outer circle). Hue varies

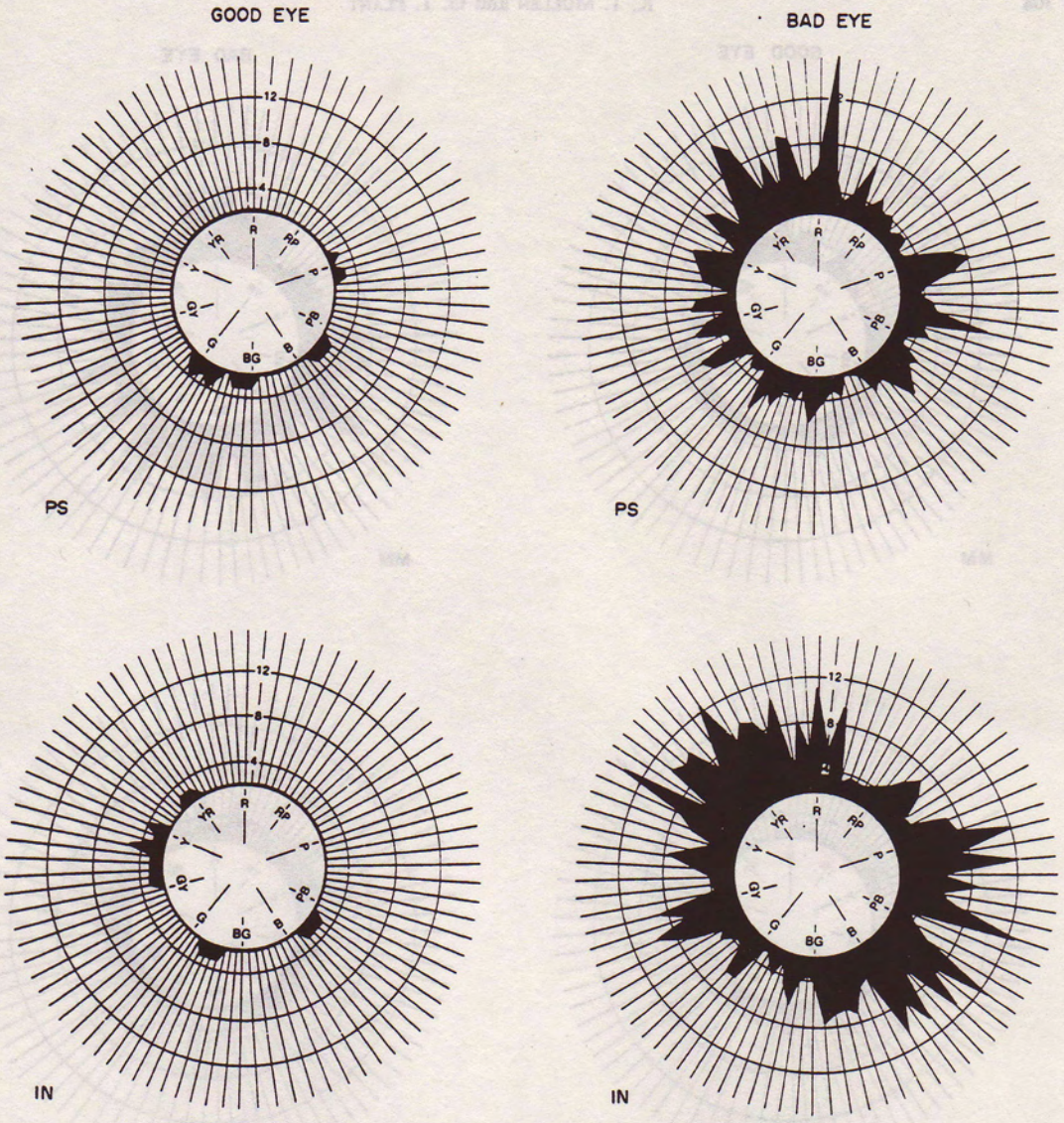

Fig. 2. The results of the Farnsworth–Munsell 100 hue test of hue discrimination on two subjects (P.S., I.N.). The left panel gives the results for the better eye and the right panel the results for the worse eye. The standard method of representing the results is used. Hue is given around the circumference and the score for hue discrimination is plotted along the radii from 2 (perfect discrimination) to 14.

around the circumference of the wheel and is given by the Munsell notations (see methods). For all the results the origin of each arrow indicates the hue and chroma of the test chip and the arrow head indicates the co-ordinates of the matching chip selected by the subject.

For each subject all the test chips are of similar chroma, within the range from 10 to 14, and similar values are used at 5 or 6 (I.N.), or at 4 or 5 (P.S., M.M.). Higher values (at 6 or 7) are used for the YR hues. Identical values and chromas at all hues cannot be used since the manufacturing process limits the available test chips (generally before the perceptual limits are reached). While a reasonably uniform representation of chroma across hue in the test chips has been achieved, this has necessitated some variation in value, and so the chroma wheels do not represent a completely uniform plane through the value space for the test chips. Marked variation occurs in the value of the matching chips selected. However, since chroma at all values is calibrated in perceptually uniform steps (see methods), the variations in value of the matching or test chips do not affect the representation of the perceived chroma or hue changes on these colour wheels.

The results of the experiments for hue and

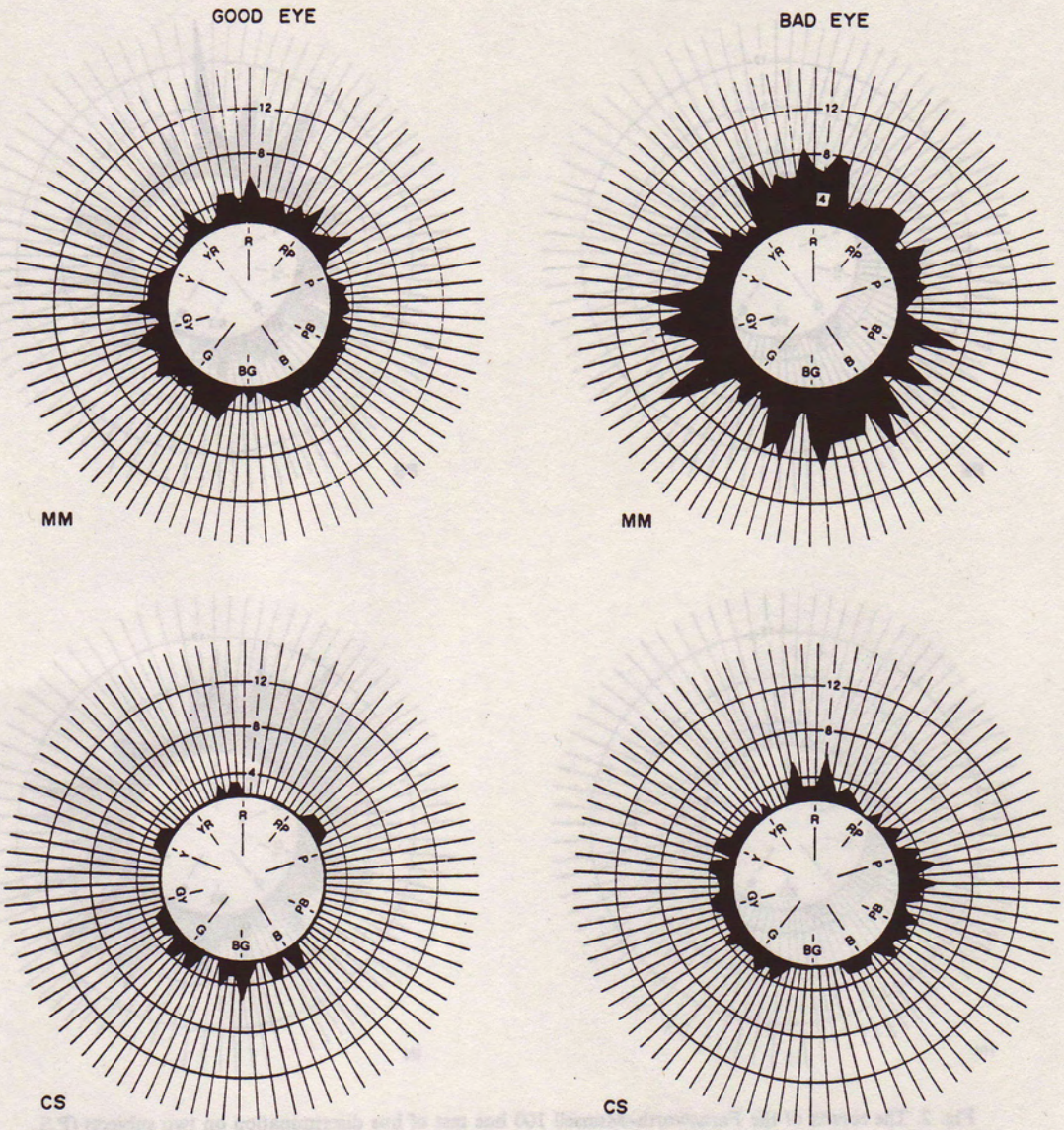

Fig. 3. The results of the Farnsworth–Munsell 100 hue test on subjects M.M. and C.S. See legend of Fig. 2 for further details.

value are shown in the lower panel of each figure. Value (height up the central axis of the colour solid) is plotted on the vertical axis. Hue is plotted along the horizontal axis and corresponds on the colour wheels shown above to the circumference of the circle at a particular chroma. Thus, this figure may be thought of as an unwrapped cylinder of iso-chroma, as described in the methods. As chroma is reduced the circumference of the iso-chroma cylinder is shortened, and this demonstrates that although hues remain perceptually equispaced, the sizes of the perceptual steps between them decrease with chroma. The test chips presented are of similar chroma (see above), however the matching chips selected are of variable chroma. Consequently, since in this figure a wide range of chroma are plotted on a single hue axis, the figure only serves to document the results and does not represent the size of the perceptual differences between hues. This aspect of the results is shown on the chroma wheels in the upper panels.

The interocular matching experiment

The greatest effects were found in three of the four subjects: P.S. and I.N. (Figs 4 and 5), and M.M. (Fig. 6). All these subjects show marked

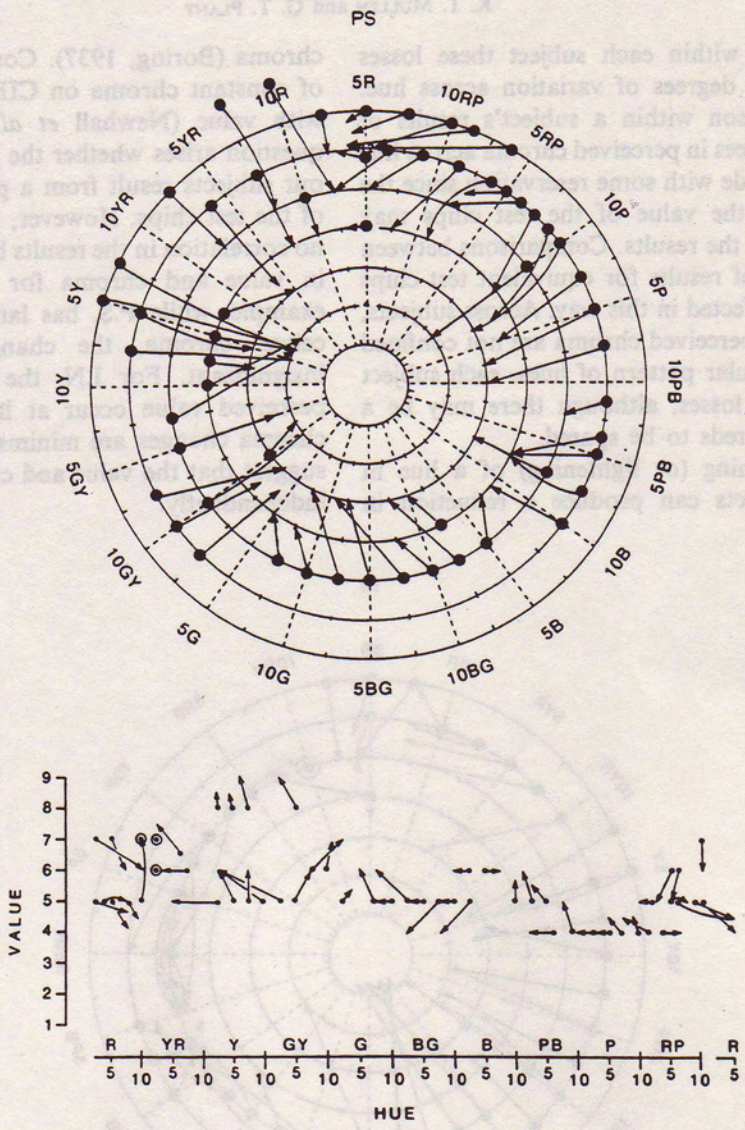

Fig. 4. The results of the matching experiment for subject P.S. The upper panel shows the results for hue and chroma: hue is given around the circumference of the wheel in Munsell notation, and chroma is given on the radii from 2 (inner circle, desaturated) to 14 (outer circle, strongly saturated). The lower panel shows the results for hue and value: hue is given on the abscissa and value of the ordinate from 1 (dark) to 9 (light). Solid circles indicate the co-ordinates of the test chip and the arrow-head indicates the matching chip. Typical standard deviations for subjects P.S., I.N., M.M. calculated for matches made three or more times are 1.4, 0.6 and 1.2 for hue, value and chroma respectively, which is considerably less than the step size between coloured chips of 2.5, 1 and 2 respectively. See text for further details.

losses in perceived chroma at most hues. P.S. had losses at all hues, these are greatest around 5 Y and least around 5 R, 5 PB and 7.5 G. The value changes are all small and across hue they average to zero. M.M. (Fig. 6) also has marked losses in perceived chroma at almost all hues. These are greatest around 5 Y and 10 GY, whereas none were found from 5 R to 5 RP. M.M. has small losses in perceived value averaging across hue to half of a value unit. Subject I.N. has large losses in perceived chroma for hues ranging from 5 BG to 10 YR which are greatest for 10 GY to 10G. However, in the other half of the colour circle from 10 BG to 10 RP there are no losses in perceived chroma. This subject shows some changes in perceived value which are uniformly distributed across hue and average 1.3 units. Subject C.S. (Fig. 7) shows very minor changes in perceived chroma and hue, and insignificant changes in value.

Thus, overall the three most severely affected subjects all showed marked losses in perceived

chroma and within each subject these losses showed wide degrees of variation across hue. The comparison within a subject's results of small differences in perceived chroma across hue should be made with some reservation since the variation in the value of the test chips may slightly affect the results. Comparisons between the subjects of results for equivalent test chips will not be affected in this way. Across subjects, the losses in perceived chroma are not confined to any particular pattern of hues, each subject has different losses, although there may be a tendency for reds to be spared.

The darkening (or lightening) of a hue in normal subjects can produce a reduction in chroma (Boring, 1937). Consequently, the loci of constant chroma on CIE co-ordinates vary with value (Newhall *et al.*, 1943). Thus the question arises whether the losses in chroma in our subjects result from a perceived darkening of the test chips. However, there appears to be no correlation in the results between the changes in value and chroma for each subject. For example, while P.S. has large changes in perceived chroma, the changes in value are insignificant. For I.N. the larger changes in perceived value occur at hues for which the chroma changes are minimal. Thus the results suggest that the value and chroma losses occur independently.

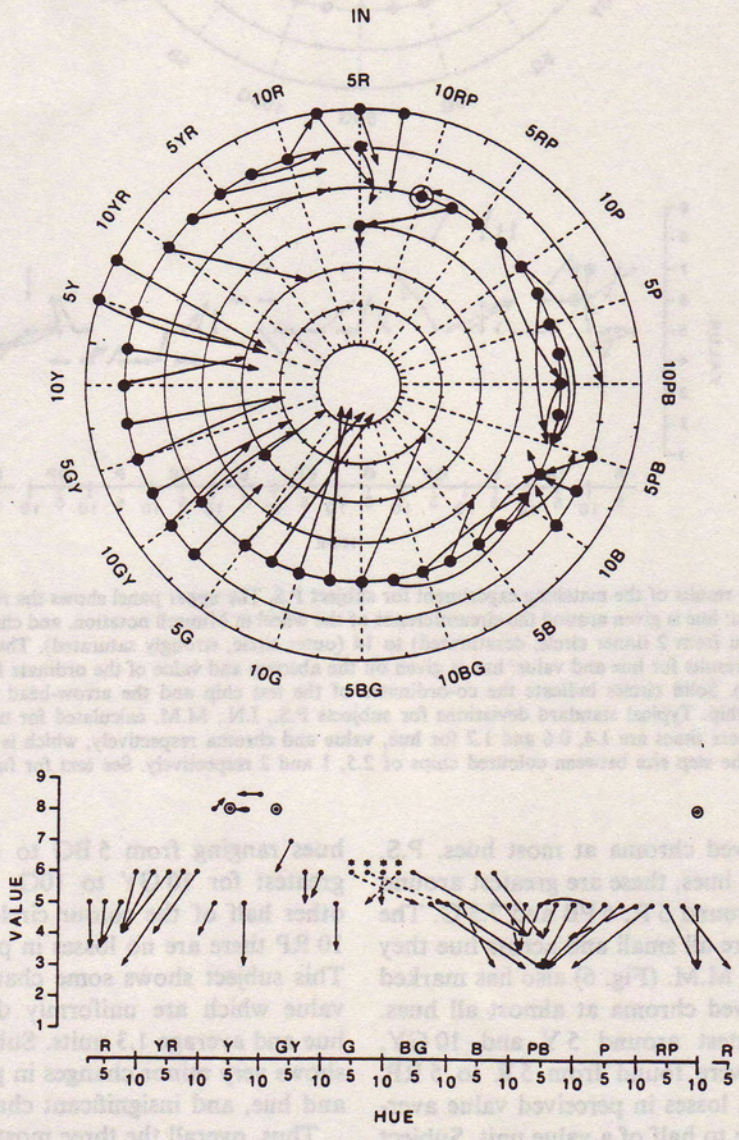

Fig. 5. The results of the matching experiment for subject I.N. An asterisk in the lower panel indicates that the subject found a hue match difficult to make due to the very low perceived chroma of the chip, given in the upper panel. See legend of Fig. 4 for details.

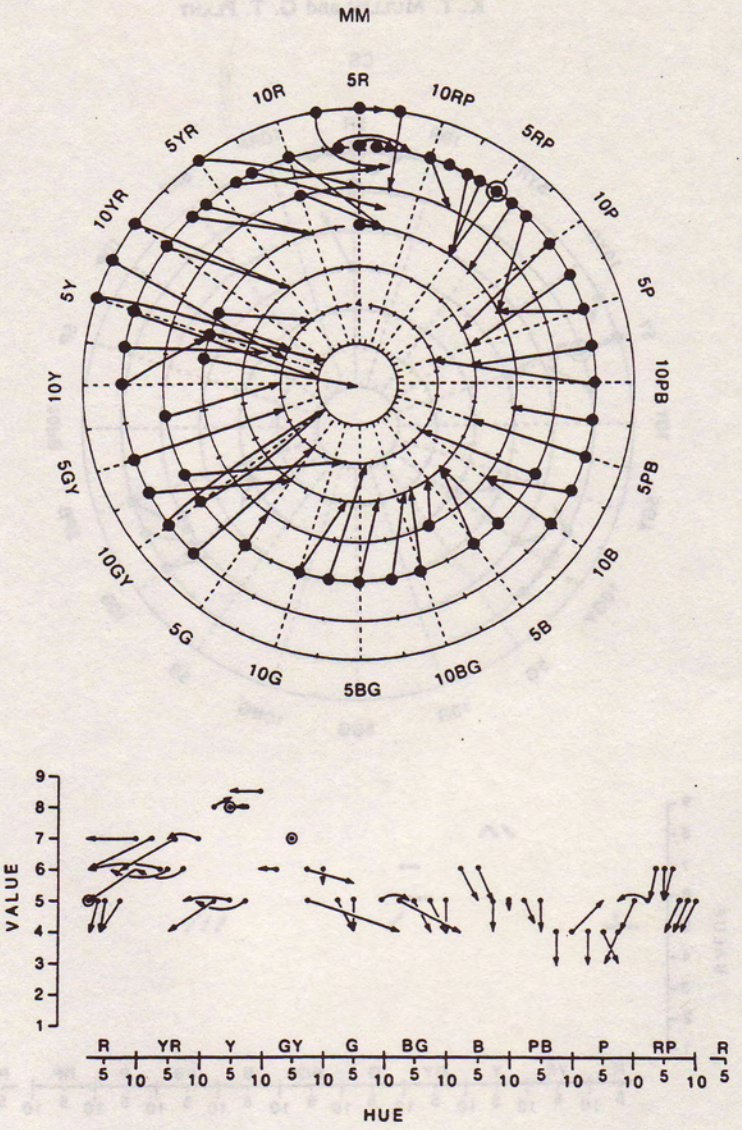

Fig. 6. The results of the matching experiment for subject M.M. See legend of Fig. 4 for details.

The three subjects (P.S., M.M. and I.N.) also have changes in perceived hue. The most striking results occur for subject I.N. All the hues in the region from 5 BG to 7.5 RP tend to be matched with those in the middle of this range (5 and 7.5 PB), revealing a hue shift which involves almost half the colour circle. Other less dramatic changes in hue are found for I.N. since hues from 2.5 YR to 5 RP tend to be matched with 7.5 or 5 R. Changes in perceived hue are also found for M.M., centered around 2.5 and 5 R. For P.S., hue changes are centered around 5 and 7.5 R and also 5 G. These main alterations in perceived hue which can be identified seem to be associated with a tendency for hues to be matched with one of the unique hues in the Munsell system, which are 5 R, 5 Y, 5 G and 5 PB (Pointer, 1982).

The changes in perceived hue can occur in the absence of any losses in perceived chroma, as for example in the case of I.N., or in the absence of any losses in perceived value, as has occurred at the BG and RP hues for P.S., or at the R hues for M.M. Any hue changes which do occur in association with large losses in perceived chroma or saturation are difficult to assess due to the constriction of the colour space at low chromas which reduces the visible differences between hues. This has occurred for example, for subject I.N. around hues of 5 G and 2.5 BG on the chroma wheel.

In normal subjects reduction in the mean

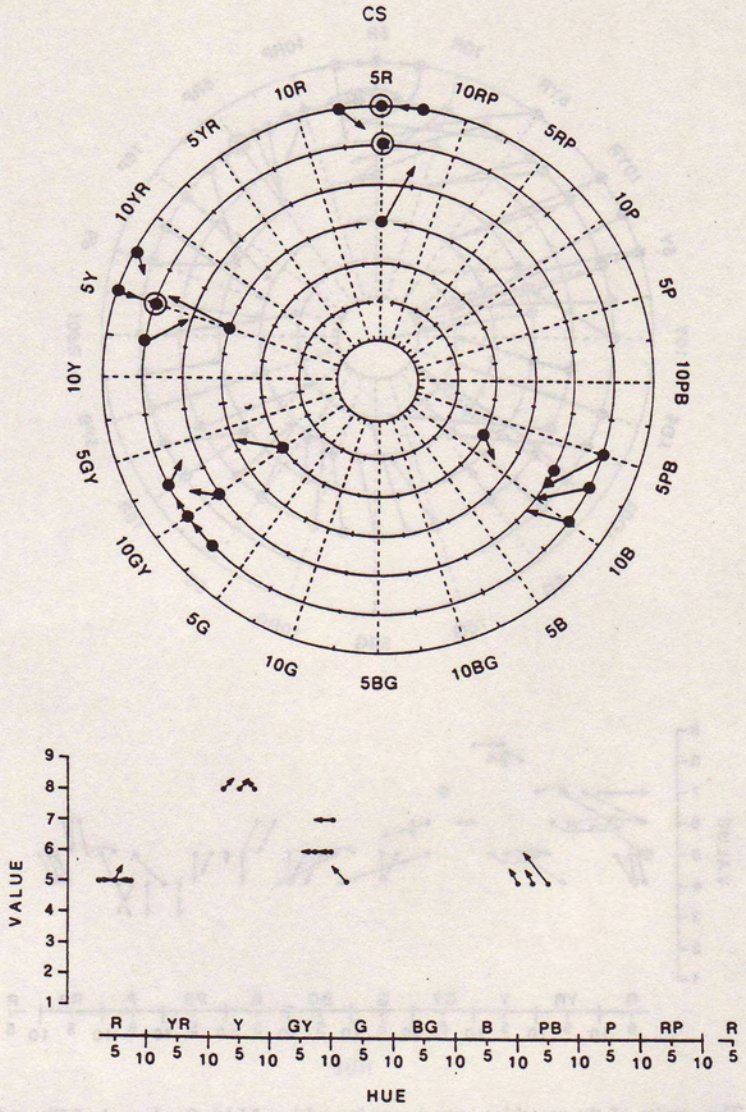

Fig. 7. The results of the matching experiment for subject C.S. See legend of Fig. 4. for details.

luminance of a chromatic stimulus may produce changes in perceived hue and this is known as the Bezold–Brücke effect (Purdy, 1931; and see Hurvich, 1981). Changes in saturation can also produce changes in perceived hue, known as Abney's effect (Abney, 1913). By producing pages of test chips of constant hue the Munsell notation of colour appearance aims to compensate for the changes in hue arising from variations in saturation or lightness. Consequently, at constant value the chromaticities of Munsell chips which are assigned the same hue on the CIE diagram mostly form curved lines joining the achromatic point to a point on the spectrum locus or the line of purples (Newhall *et al.*, 1943; Wyszecki and Stiles, 1967). The effect of lightness on the hue of surface colours is also demonstrated on the CIE coordinates since loci representing constant hue at different values are mostly not coincident, but form clusters (Newhall *et al.*, 1943). One possibilility which arises is whether the hue shifts in our subjects occur as a consequence of any changes in perceived value or chroma. This might result because the value or chroma losses in our subjects, which have a neural origin, affect hue appearance differently from chroma or value changes with a physical origin. In this case, the larger chroma or value changes in the subjects would be associated with the larger changes in hue.

In Fig. 8 the change in hue for each subject is plotted as a function of the loss in chroma

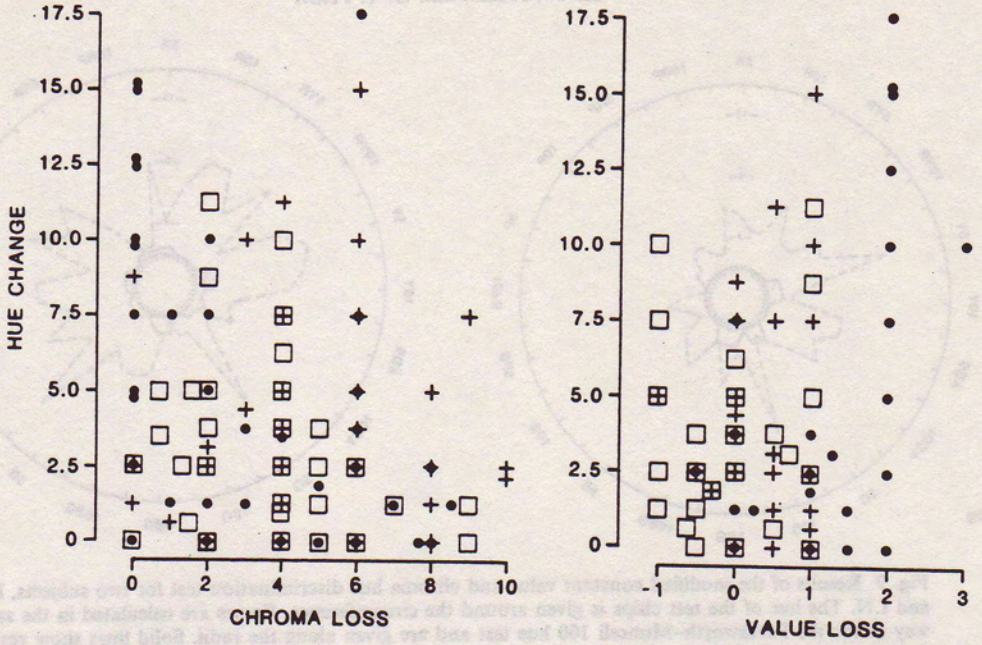

Fig. 8. The difference in hue between test and matching chip was calculated from the Munsell notation (a difference of 2.5 corresponds to a hue shift of one page), and is given on the ordinate. In the left panel chroma loss, in Munsell units of chroma, is plotted along the abscissa and in the right panel value loss, in Munsell units of value, is given on the abscissa. Results for three subjects are shown: ●, I.N.; □ P.S.; +, M.M.

(left panel) or the loss in value (right panel). The results show that there is no association between the size of the hue change and the chroma loss or the value loss. Thus these results indicate that the hue changes in our subjects occur independently and do not arise from a reduction in perceived value or chroma.

A test of hue discrimination

One question which arises is whether the errors on the Farnsworth–Munsell 100 hue test shown in Figs 2 and 3 can be accounted for by the large losses in perceived chroma in the affected eyes, or whether other independent deficiencies in hue discrimination exist. Reductions in perceived chroma effectively contract the colour space and reduce the visible increments in hue between the test colours on the Farnsworth–Munsell test, and so are likely to increase the errors made. Likewise, losses in perceived value may also increase errors in hue discrimination.

To address this question a modified hue discrimination test was devised for each eye of each subject by using an array of 40 chips of different hues selected from the Munsell Book of Color. For the modified test the variations in chroma and value in the bad eye revealed in the matching experiment were eliminated by selecting test chips equated for chroma and value for that eye, at appropriately spaced intervals of hue. Test chips with a value and chroma of 5/2 were viewed with the good eye of each subject and the bad eye was used, in a between-eye match, to select chips of matching chroma and value. An array of test chips was selected of 40 different hues which appeared as the same, uniform value and chroma to each of the subject's eyes. Thus, errors in discriminating between these hues are likely to arise from genuine deficiencies in hue discrimination rather than from the losses in value and chroma. Subjects were asked to align the chips in order of changing hue under the same experimental conditions as were used for the Farnsworth–Munsell 100 hue test. Results are given in Fig. 9 for subjects P.S. and I.N.

The hue of each test chip is given around the circumference of the circle, and the radii indicate the errors made on the test, using the same method of calculation as for the Farnsworth–Munsell 100 hue test. The results for both subjects (P.S., I.N.) indicate that much greater error scores are found for the affected eyes than for the unaffected eyes. When the variations in chroma and value in the bad eye are eliminated

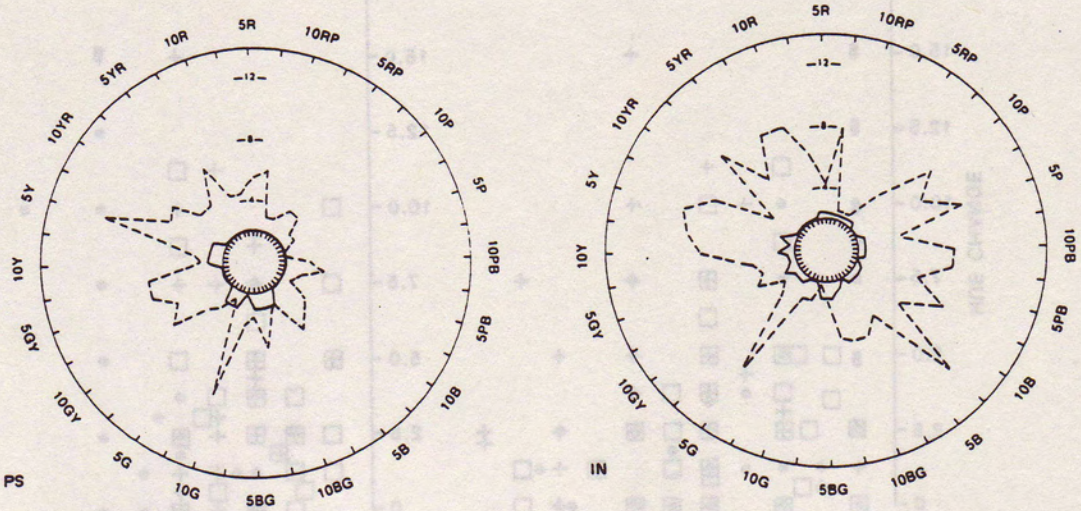

Fig. 9. Results of the modified constant value and chroma hue discrimination test for two subjects, P.S. and I.N. The hue of the test chips is given around the circumference. Errors are calculated in the same way as for the Farnsworth–Munsell 100 hue test and are given along the radii. Solid lines show results for the better eye and dashed lines give results for the worse eye of each subject. Test chips for the good eye were presented at a value and chroma of 5/2, and test chips presented to the bad eye had previously been matched to these in value and chroma.

large errors in hue discrimination remain, whereas the unaffected eye, which views chips at the same value and chroma as the affected eye, makes very few errors. The results indicate that the errors made by the affected eyes arise from primary deficits in hue discrimination and are not produced by the reductions in chroma or value. The results for I.N. show the same red-green axial loss of hue discrimination which was apparent in the results of the Farnsworth–Munsell 100 hue test (Fig. 2).

DISCUSSION

Hue discrimination

Losses in colour discrimination in recovered and chronic optic neuritis have previously been assessed using the Farnsworth–Munsell 100 hue test (see Foster, 1986 for review; Burde and Gallin, 1975; Griffin and Wray, 1978). Griffin and Wray (1978) consider this test to be one of the most sensitive in detection of optic nerve disorders, and they find that high error scores occur even when visual acuity is normal or close to normal. Also commonly suggested is that deficits in hue discrimination occur along a red/green axis. The basis for this idea first arose from Köllner's rule for acquired colour vision defects (1912) which holds that while blue is affected by retinal disorders, red/green deficits are characteristic of optic nerve disorders, and in general this rule is still considered to be valid today (see Pokorny and Smith, 1986 for a critical discussion). Red/green deficits have been reported on the Ishihara test for colour deficiencies (Glaser, 1976; Lynn, 1959), but since this test does not include tritan plates, comparisons between red, green and blue defects have not been made. In the classification of acquired colour vision deficiencies developed by Verriest (1963), red/green defects in colour discrimination (termed type II defects) are associated with milder optic nerve disorders including optic neuritis, whereas additional blue defects occur in the more severe cases. In the Wald–Marré classification of acquired colour vision disorders, using spectral colour discrimination (Marré, 1973) optic nerve disorders are classified as type IIa and IIb, corresponding to the mild and severe Verriest type II classification, and are associated with predominant red and green deficiencies (see Pinkers *et al.*, 1979; Chisholm, 1979; Pokorny and Smith, 1986).

The results of the Farnsworth–Munsell 100 hue test on the 11 affected eyes of our subjects confirm that recovered optic neuritis is associated with abnormally high error scores. We found that in our population of eyes, errors were distributed across all hues and we found no evidence for systematic red/green or blue/yellow axial losses of hue discrimination. In one eye a

red/green axial loss was indicated although this was not strongly pronounced.

The results of the modified version of the hue discrimination test (Fig. 9) indicate that there is evidence for a primary loss in hue discrimination which has not arisen as a consequence of any reductions in perceived chroma or value of the test chips. Overall, the results of our investigation of hue discrimination indicate that in the case of optic neuritis there are notable exceptions to Köllner's rule and the Verriest and Wald–Marré classifications of optic nerve disorders.

The interocular matching experiments

Subjects with optic neuritis frequently report that colours appear duller or washed-out in their affected eye, and these descriptions have been taken to indicate a loss of saturation and/or brightness in the affected eye (Glaser, 1976; Burde, 1975). Subjective comparisons of the appearance of a red test disc between the two eyes of a patient is used as a clinical test of optic nerve damage (Glaser, 1976). Our results provide a quantitative assessment of these reports. We find that the saturation (chroma) of colours can be much reduced in the affected eyes, and for any one subject this effect may occur only at particular hues. Comparisons between our subjects indicate that losses in chroma are not confined to any consistent pattern of hues. Value (brightness) was reduced in some, but not all subjects. Again for an individual subject, specific hues can be affected but no consistent pattern of losses across hue in the different subjects emerged. Previous work has indicated that optic neuritis produces deficits in luminance contrast at suprathreshold levels (Hess, 1983). The value changes we report are probably the result of both changes in perceived contrast, affecting the relative brightness of the test chip against the white background, as well as changes in the mean luminance of the test chip and background. The independent contribution of these two effects is difficult to assess.

Marked changes in the appearance of hues also occurred in the affected eyes, and the results indicate that these are a primary effect, not arising from losses in chroma or value. It is an interesting result that in our subjects hue changes are not found in association with the perceived darkening or desaturation of the test stimuli. It has already been emphasised that in order to produce pages of uniform hue at all lightnesses and saturations, the Munsell book compensates for the normal changes in hue associated with the darkening and desaturation of stimuli (the Bezold–Brücke and Abney effects respectively). The observation that our subjects do not generally show a shift in their Munsell hue matches associated with the perceived losses in value and chroma indicate the presence of the normal Bezold–Brücke and Abney effects. Thus, it appears that these effects may arise from a darkening or desaturation of the test stimuli which is neural in origin, as well as by the actual physical darkening or desaturation of stimuli.

The data suggest that if hue changes occur, the hues in the affected eye tend to be matched with one of the four unique hues on the Munsell system. Hue changes occurring at one unique hue were not predictive of those occurring at any other. Overall, in the four subjects which were investigated there is no evidence for selective changes in hue, chroma or brightness being consistently associated with the red or green hues in optic neuritis as Köllner's rule, and the Verriest and Wald–Marré classifications of optic nerve disorders claim.

Previous studies have shown that colour deficits occur at visual threshold in optic neuritis (Alvarez *et al.*, 1982; Foster *et al.*, 1985; Fallowfield and Krauskopf, 1984; Mullen and Plant, 1985). There is evidence that the threshold detection of increments in saturation from white is more severely affected than detection of incremental changes in luminance (Fallowfield and Krauskopf, 1984). Mullen and Plant (1985, and in press) have shown that deficits in colour contrast sensitivity are generally greater than deficits in luminance contrast sensitivity, and in particular the subjects (I.N., P.S., M.M.) have a selective loss of colour contrast sensitivity. Thus the suprathreshold deficits revealed in these three subjects are coupled at threshold with a selective loss of colour contrast sensitivity.

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