Saturation-Specific Pattern of Acquired Colour Vision Deficiency in Two Clinical Populations Revealed by the Method of Triads

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Abstract: Subjective colour spaces were reconstructed for persons occupationally exposed to mercury (Hg) and patients with diabetes mellitus type 2, two groups at risk for acquired colour-vision deficiency, and compared with healthy normal trichromats. Judgments of colour dissimilarity were collected with the method of triads, applied to a composite assortment of colour samples. These were drawn from two widely used colour arrangement tests-10 hues from the Farnsworth D-15 test and five from the Lanthony Desaturated D-15d test, ensuring that the assortment sampled two levels of lightness and saturation. The data were analyzed with maximum-likelihood multidimensional scaling (MDS) and within a novel individualdifferences MDS model to estimate subject-specific parameters. The MDS solutions for the two clinical groups showed a compression along a blue-yellow axis, limited however to desaturated hues. This result was confirmed by the individual-differences model. In addition, the clinical groups were found to place significantly higher

weights on the lightness differences between stimuli, conceivably to compensate for their reduced chromatic discrimination. The specific form of colour-space distortion in the clinical groups indicated an increase in their thresholds for blue-yellow signals, providing insights into the nature of impairment mechanisms. The results have implications for stimuli and diagnostic procedures for testing individual differences in color vision, and for analyzing the responses. This approach is sensitive to distinctive patterns of subtle colour-vision impairment underestimated by the conventional D-15d test. © 2013 Wiley Periodicals, Inc. Col Res Appl, 39, 125–135, 2014; Published online 5 February 2013 in Wiley Online Library (wileyonlinelibrary. com). DOI 10.1002/col.21794

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INTRODUCTION

The D-15 and D-15d are two widely used tests for detecting and quantifying deficits of colour perception.^{1,2} Both are 'panel tests' in which 16 coloured samples, located by their

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specifications in colour space so as to form an incomplete circle, must be arranged into the correct rainbow sequence. In each case, an error score measures overall loss of colour discrimination. These tests also qualify the nature of colour vision loss, distinguishing blue-yellow (B/Y) and/or redgreen (R/G) impairment. Their advantages include speed and convenience; the D-15d, in addition, is sensitive to mild forms of colour vision impairment. The D-15 is designed for classifying an individual within the diagnostic taxonomy of congenital colour vision deficits, determining the 'polarity' of the deficiency, that is B/Y or R/G, if it exceeds a threshold of severity. The D-15d lends itself well to assessing acquired deficits where early detection of a progressive impairment can be crucial, and is less clear-cut, that is the breakdown by polarity is often less clear than for congenital deficiency. For these reasons, the D-15d sees applications in many clinical studies³⁻⁵ as well as in the area of occupational optometry, where deficits may be the result of work-related exposure to toxins.⁶

From one perspective, a subject's responses to panel tests such as the D-15 and D-15d can be regarded as a ranking of the pairwise dissimilarities among the colour samples, from most-similar to the least-similar pair.⁷ A subject may approach the samples with some alternative procedure—sorting them into groups, for instance—and as long as the responses can be treated as comparisons amongst dissimilarities, they can be analyzed within the same over-arching framework.

Bimler et al.⁸ used the method of triads⁹ to elicit 'oddone-out' data for a combined set of D-15 and D-15d samples, presenting a series of triadic combinations to each subject who had to choose the least similar sample from each three. Most combinations require saturated, darker stimuli from the D-15 to be considered against desaturated, lighter ones from the D-15d, so the odd-one-out choice may vary if the observer places more weight on either hue or lightness differences. In addition, a triad might probe similarities at the scale of barely discernable differences (as with the D-15d) or at a coarse, suprathreshold scale (with D-15), depending on its constituent samples. Analysis of the data with multidimensional scaling (MDS) allows a subjective colour space to be reconstructed for each individual or certain groups of individuals.¹⁰ This analysis of similarity data from the combined colour samples has revealed subtle differences, for example, between smoking and nonsmoking groups,¹¹ monozygotic and dizygotic twins,¹² between females and males⁸ and between homozygous females and heterozygous carriers of colour vision deficiency.13

For clinical populations, Feitosa-Santana *et al.* elicited odd-one-out responses of this form—for randomised triads of a combined D-15 and D-15d stimulus set—for age-matched normal controls and groups whose colour vision had potentially been impaired by exposure to mercury vapor¹⁴ or by diabetes mellitus type 2 (DM-2).¹⁵ For convenience, although without losing generality or statistical power, the triads in these studies did not follow a predetermined list, but rather were generated randomly.

The MDS solutions for both clinical groups^{14,15} revealed distributions significantly different from those in the respective control groups. The clinical groups' colour spaces tended to show a greater level of distortion and higher variability in the locations of stimuli along the B/ Y axis, that is possible tritan-type polar deficiency with a B/Y confusion axis.

In this study, we are interested in whether the variations between individuals-and between clinical and control groups-take the form of relative insensitivity along specific directions in colour space, as a specific loss of sensitivity can provide clues to the neural locus (or loci) of the visual system implicated in an acquired deficiency. As Krastel and Moreland (Ref. 16, p. 117) note, "... acquired tritan deficits may be subjectively quite unobtrusive and well tolerated'; that is, decreases in hue discrimination (i.e. increased thresholds) do not necessarily affect subjective colour experience or reach the level of awareness. The method used here allows for the possibility of capturing subtle hue discrimination impairments using relatively desaturated stimuli along with saturated ones. Thus, subjects are required to consider small hue differences (close to threshold) between relatively similar pairs of stimuli, as well as larger, supra-threshold differences.

In the geometrical paradigm, a polar deficiency is represented as a compression of colour space.¹⁰ Here, this was tested by reanalysing the data of Feitosa-Santana *et al.*^{14,15} within the framework of individual-differences MDS. The latter imposes a single geometrical solution upon all the subjects, while allowing that solution to vary in a particular way (compression along a confusion axis) controlled by a small number of parameters, to fit it to each subject's responses. A subject's data are thereby boiled down to their values of the parameters.

Acquired Colour Vision Impairment and Occupational Mercury Exposure

Mercury, both in its elemental form (e.g. mercury vapour) and as an organic compound (methylmercury), is a potent neurotoxin that can cause a range of perceptual, motor and cognitive impairments.^{17–20}

Inter alia, mercury exposure is known to affect colour vision.^{21–23} The impairment manifests itself, in particular, as increased colour discrimination thresholds and decreased chromatic contrast sensitivity.^{24,25} As Pokorny *et al.* (Ref. 26, p. 309) note, '[a] generalized depression of optic nerve conduction characterised by peripheral constriction of the visual fields and optic atrophy is a clinical picture found in [...] mercury toxicity (Minimata disease)'. In the periphery of the visual system, impairment of inner and outer retinal function was found, indicating damage to postreceptoral structures.²⁵ Nor can damage to the visual cortex be excluded.^{27,28} Estimating specific loss of sensitivity, that is delineation of the confusion axes in colour space, can provide clues to the neural locus (or loci) affected by mercury.

The D-15d test revealed higher error scores in mercury exposed persons, with a higher frequency of blue-yellow confusion (type III dyschromatopsia, according to Verriest's classification²⁹), regardless of whether they were exposed occupationally^{21,23} or via contaminated food.^{18,19} Employment of the Farnsworth-Munsell 100-hue test (FM-100) showed that mercury-contaminated subjects performed significantly worse than matched controls, but revealed no distinct confusion axis in colour space.²⁴

When tested with the Cambridge colour test (CCT),³⁰ subjects exposed to mercury revealed increased chromatic discrimination thresholds along all three confusion axes (protan, deutan and tritan) and nonselective enlargement of MacAdam ellipses. These findings related to gold miners,²⁴ workers in the fluorescent-tube industry (Feitosa-Santana *et al.*)^{25,28,31} and dentists, exposed through dental amalgam.³²

Development of Colour Vision Impairment in DM-2

The sequelae of diabetes mellitus include colour vision impairment: persistent hyperglycemia causes retinal microvascular changes that damage the retina (diabetic retinopathy, DR), leading to losses in visual acuity (VA) and contrast sensitivity as well as in colour vision.³³ In diabetic patients, elevated thresholds for cone photoreceptors have been reported and attributed to the concentration of circulating glucose and a reduction of the oxygen supply.³⁴ Notably, subclinical or mild colour vision impairment may precede DR to emerge at early stages of DM-2, before the appearance of vascular alterations.

Colour vision of DM-2 patients was examined in many studies using panel tests, such as the FM-100^{35–37} as well as D-15 and/or D-15d test.^{15,38} Anomaloscopy has been used to estimate Rayleigh and Moreland matches for the two perceptual systems, R/G and B/Y, respectively.³⁹ Crucially, the extrapolation from anomaloscope matching range to colour impairment is far from direct. More recently, the CCT has been used to estimate colour discrimination thresholds along the protan, deutan and tritan confusion lines.³⁸

An effect on the B/Y, or tritan system, is repeatedly found in DM-2 patients. In patients without DR, predominantly tritan losses were diagnosed³³; however, diffuse losses were reported as well.^{40,41} In DM-2 patients who had developed DR, losses in the B/Y system were found to increase with severity of DR.^{33,42–44}

Feitosa-Santana *et al.* assessed colour vision impairment in DM-2 patients without DR.^{15,38} This study re-examines those data.

METHOD

Subjects

All patients and controls underwent an ophthalmological examination, with the following inclusion criteria: best corrected Snellen VA 20/30 or better; absence of retinopathy, ocular disease and posterior sub capsular cataract; maximum of grade 1 for cortical opacity (C1), nuclear colour (NC1) and nuclear opalescence (NO1) following the lens opacity classification system III. Clinical histories were collected to exclude alcoholism, smoking and systemic diseases that could affect the visual system. Observers with congenital colour deficiency were excluded using the D-15 test.

The mercury (Hg)-exposed group included 22 subjects who had been exposed to Hg vapor for at least 5 years working in fluorescent lamp industries. All had been discharged from work at least 1 year earlier and placed on disability retirement due to medical diagnosis of Hg intoxication based on clinical and laboratory examination. They had been referred by the Occupational Health Service of the Oscar Freire Institute of the University of São Paulo (Brazil). Table I in Ref. 14 tabulates details for 18 of these subjects (13 males), aged 42.1 ± 6.5 years; the four additional subjects had similar demographic characteristics.

The DM-2 group consisted of 32 patients (18 males), aged 30–76 years (50.5 ± 10.7), with disease duration from 0.5 to 27 years (9 ± 8.6). The absence of retinopathy was verified by fundoscopy (in 100% of the eyes) and by fundus photography and fluorescein angiography (62% of the eyes were examined; 100% of these lacked any sign of retinopathy).^{31,38}

Twenty-three observers (15 males), aged 35–80 years (51 \pm 12), served as controls. An age-matched subset of 18 of these observers were used as controls in Ref. 14 (Table II), and 20 as controls in Ref. 15; age-matching was less rigid in the present analysis.

Procedure

The D-15 and D-15d tests each consist of 16 colour samples (plastic caps holding 12-mm circles of pigment on paper), occupying an incomplete circle in colour space. In Munsell denotation, the D-15 caps have value=5 and Chroma=4;¹ the D-15d caps have the same hues but are lighter, with value=8, and less saturated, $Chroma=2.^{2}$ Because of the lower saturation of the D-15d stimuli, differences between them are closer to threshold.^{3,4,45} A composite assortment of 15 caps was created from the D-15 series by replacing caps No. 3, 6, 9, 12 and 15 with their counterparts from the D-15d and excluding the 'pilot' caps, which were anchored to the test trays. This assortment was shuffled into five randomised groups of three. The subject viewed each triad in turn and chose the most dissimilar cap of the three (the odd-one-out).

No time limit was set. This procedure was repeated 12 times. The subject also judged five random triads created by shuffling the D-15 caps and five from the D-15d caps, providing a total of 70 triad judgments.^{11,12} At the beginning of the session, the D-15 and D-15d caps were both used in the traditional way: the subject arranged them in a colour sequence, starting with the pilot cap and following each cap with the cap most similar to it.

The procedure was conducted monocularly. Control subjects were tested in only one eye. Subjects from the

clinical groups repeated the procedure for both eyes (with random choice of testing left or right eye first) as acquired colour discrimination loss is not necessarily symmetrical.²⁹ Thus, the 15 caps comprising the composite assortment were viewed 13 times by each control subject and 26 times by each clinical subject. The 10 D-15d and five D-15 caps were viewed once by each control subject (in the five desaturated-only and five saturated-only triads, respectively) and twice by each clinical subject.

Illumination of 500 lux was provided by two fluorescent lamps (Sylvania Octron 6500 K FO32W/65K), with coordinated color temperature=6500 K, color rendering index=75).

MDS Analysis

We set out to reconstruct multidimensional colour spaces in which points represent the hues and are located so that the spatial distance between any two points reflects the perceived dissimilarity between that pair of hues. Each triad of caps corresponds to a triangle of points, in which the apex should be the hue chosen as odd-one-out.

For an initial exploratory analysis, the subjects' data were combined within each group and analyzed with the existing 'MTRIAD' software $^{11-14}$ to obtain three separate solutions, that is consensus colour spaces for the controls, Hg and DM-2 groups. MTRIAD applies a maximum-likelihood algorithm, similar to the MAXSCAL algorithm for dissimilarity comparisons.⁴⁶ A likelihood function LL(X)quantifies the agreement between the solution and the individual triads comprising the data. LL(X) is maximised in an iterative process that begins with initial estimates of the coordinates locating 30 points in the space, then adjusts them to progressively converge on a solution in which the interpoint distances are more likely than any other combination of distances to have produced the observed odd-one-out decisions. The Appendix provides more detail (see also Ref. 7). A similar logic, in one dimension, features in maximum-likelihood difference scaling.47,48 MTRIAD is available from the corresponding author.

To foreshadow the Results: constrained three-dimensional solutions were chosen for each group as we found that three dimensions provided a substantial improvement in likelihood compared to two dimensions, whereas the addition of a fourth dimension brought little further improvement. As expected, the first two dimensions lent themselves for interpretation as perceptual colour-opponent systems, R/G and B/Y. The third dimension was interpretable as variation of lightness (value) among stimuli.

Each solution can be written as a 30-by-3 matrix **X**, where the *i*th row contains the coordinates $\{x_{i1}, x_{i2}, x_{i3}\}$ that locate that hue along the three dimensions of the colour space. Sometimes a MDS solution can be rotated to bring its axes into correspondence with the familiar colour dimensions, so that the contribution from two points' separation along the first axis (i.e. $x_{i1}-x_{i1}$) corresponds to

their displacement along (e.g.) the R/G dimension, and so on. This cannot be assumed in advance, however.

When the three group exploratory solutions were compared (as detailed below), they gave the impression that subjects in the clinical groups tended to be less sensitive to blue-yellow colour differences, resulting in a compression of colour space along the corresponding axis, but only for the desaturated hues. This impression was quantified in a confirmatory stage, analysing each subject's data in isolation.

Confirmatory Analysis

Our previous research with the same method and hues and a larger pool of subjects (Fig. 1 of Ref. 12) provided X_0 , a 'standard' matrix of coordinates in a default, consensus colour space. In this analysis, X_0 was distorted (compressed) to produce individual colour spaces X_m tailored to the *m*th subject's responses. This entailed two subject-specific parameters, w_{m2} and w_{m3} (or two parameters for each eye of subjects in the clinical populations).

For each individual space X_m , w_{m2} is the weight or salience of the second dimension relative to the first dimension: $x_{mi2}=w_{m2} x_{0i2}$ (where the index *i* labels the hues). Because X_0 has been rotated so that its second dimension corresponds to the tritan confusion axis, values of $w_{m2}<1$ indicate blue-yellow (tritan) deficiency, ranging in severity, with its extreme form, tritanopia, indicated by $w_{m2}=0$ (i.e. subject *m* would see no distinction between two hues that differ only in stimulation to the S-cones, and are separated only along the B/Y axis). Conversely, $w_{m2}>1$ results if the *m*th subject is relatively insensitive to red-green differences, with larger values indicating increasingly severe R/G deficiency.

So far we follow a number of precedents. However, in a departure from that research tradition, the model tested here only imposes w_{m2} upon the locations of the desaturated hues—with the saturated hues retaining their default values of x_{0i2} —based on the evidence that any acquired colour deficiency disproportionately affects discrimination of desaturated colours.

Recall that the desaturated D-15d caps differ from those of the D-15 series in lightness (value). Combined with the range of hues, the lightness differences require a third dimension to accommodate them within the solutions from the exploratory analyses. X_0 is likewise threedimensional, with the D-15 and D-15d points occupying two parallel planes. Notably, subjects can vary in the weight they place on lightness differences in their dissimilarity perceptions.^{49,50} The parameter w_{m3} accommodates these variations through the equation $x_{mi3} = w_{m3} x_{0i3}$.

The two parameters, w_{m2} and w_{m3} , were adjusted systematically, summing LL(\mathbf{X}_m) for each combination, to find the particular values that maximised the fit between \mathbf{X}_m and the *m*th dataset. The distributions of w_{m2} and w_{m3} within each subject group can be compared among the

control and two clinical groups, and any differences tested for significance.

RESULTS

MDS Analysis

We examined two-dimensional and three-dimensional MDS solutions for each subject group. In each case, the third dimension was interpretable (after rotation) as lightness or value, arranging the points in two roughly parallel planes in space. To reduce the degrees of freedom and for ease of display, we also examined constrained solutions in which the darker D-15 caps (V=5) all shared a single coordinate on the third dimension (i.e. the mean around which they cluster), and the lighter D-15d caps (V=8) all shared a second common coordinate.

The log-likelihoods for 2D solutions for the controls, Hg and DM-2 groups were LL(**X**)=-848, -2420 and -3650, respectively. For constrained 3D solutions with one additional degree of freedom, the corresponding values were -794, -2070 and -3380, the improvements being Δ LL=54, 350 and 270. According to the likelihood ratio test, 2 Δ LL follows a χ^2 distribution, so the improvements are all significant (*P*<0.001).⁴⁶ Unconstrained 3D solutions (with another 26 degrees of freedom) bring LL(**X**) up to -753, -1990 and -3295. Although smaller, the further improvements Δ LL=41, 80 and 85 are all significant, that is the third-dimensional coordinates do depart from the two parallel planes.

Figure 1 shows the constrained 3D solutions, labeled for convenience X_C (controls), X_{Hg} and X_{DM-2} . Oblique perspectives are shown in the left-hand panels. The right-hand panels show projections on the first two dimensions, which can be interpreted as Red-Green (D1) and Blue-Yellow (D2) gradients. Consistently, the saturated and desaturated colours are each arranged in a rough horseshoe (shown by solid and dotted lines, respectively), following the expected sequence from Purple (5P) through Red (5R), Yellow (5Y) and Green (5G) through to Blue (5B). The 15 stimuli comprising the 'composite assortment' are localised more tightly than the other 15, because (as noted in the Procedure) they were triangulated by appearing in 13 times as many triads. The stimuli excluded from the assortment are localized in the top, middle and bottom panels of Fig. 1 by 23, 44 and 66 triads, respectively, and their confidence bounds would be looser.

The constrained MDS confines the stimulus-points to two planes—separated by the third dimension, lightness, or value (D3)—as shown in the left-hand panels. These planes contain, respectively, the darker/saturated stimuli (value=5, chroma=4) and the lighter/desaturated stimuli (value=8, chroma=2).

The right-hand panel for control normal trichromats (X_C) shows the two stimulus sequences spanning similar ranges of the first two dimensions. That is, corresponding dissimilarities among saturated and desaturated colours are seen as comparable, even though the former are twice as far from White as the latter in Munsell terms (chroma=4 vs. 2) or greater in CIE1931 terms (see Fig. 2 of Ref. 5). This is not unexpected, as in earlier results other groups of normal trichromats were equally willing to discount saturation.^{8,11}

There is a crucial contrast in the two clinical population solutions, X_{Hg} and X_{DM-2} . There, both sequences are spread out equally along the R/G axis, but the desaturated stimuli do not seem to occupy as much of the B/Y axis as do the saturated stimuli. That is, the arrangement of desaturated stimuli is elliptical rather than circular. In addition, the gap separating the desaturated stimuli from saturated stimuli along the lightness dimension *D*3 appears to be larger (left-hand panels).

These visual impressions can be tested by examining the dispersal of points along each axis of the MDS solution (i.e. the variance of coordinates along each axis), as a fraction of total variance (Table I). D1 disperses the stimuli by about the same extent in all three solutions. However, compared to the controls, the dispersal for the clinical groups is smaller along D2 (Blue-Yellow), with a compensatory increase along D3 (value). More specifically, when we partition the D2 dispersal into separate contributions from the saturated and desaturated stimuli, the decrease in the two clinical groups is confined to the desaturated component.

Note that this kind of saturation-dependent effect does not conform to the assumptions of the weighted-Euclidean model of individual differences. Intersubject variations of this form can be modeled within the weighted-Euclidean framework, but the resulting dimensional-salience parameters will be a compromise between saturated and desaturated stimulus sets.

Confirmatory Analysis

To disentangle the dissimilarity impact on saturated and desaturated colours, individual subjects' responses were fitted separately for a model of individual variation suggested by Fig. 1, in which a parameter w_{m2} tailors a standard colour space X_0 by varying the B/Y contribution to interitem dissimilarity, but only for the desaturated stimuli. A second parameter w_{m3} reflects the dissimilarity contribution from lightness differences. The distributions of the parameters are plotted as histograms for each group in Fig. 2. Values of w_{m2} were lower across the clinical groups compared to the controls (P=0.004), to the extent that many subjects appeared to be oblivious to the blueness or yellowness of desaturated stimuli. The group differences remained significant when comparing controls to the DM-2 group, but not to the Hg group separately (Table II); the two clinical groups did not differ significantly.

When presented with triads that comprised one (or two) lighter/less saturated stimuli and two (or one) darker/saturated stimuli, the Hg and DM-2 subjects also attended more than the controls to lightness when choosing the odd-one-out, as reflected in higher w_{m3} values (Fig. 2, bottom). The difference in the w_{m3} distributions was significant between the control and both clinical



FIG. 1. The three-dimensional MDS solutions for triadic data from controls (top), mercury (Hg)-exposed subjects (middle) and diabetes (DM-2) patients (bottom). Perspective views (left) and projections on the first two dimensions (right). — darker/saturated D-15 caps; •••• lighter/desaturated D-15d caps. The labels of caps along the desaturated sequence in right-hand panels are omitted for the sake of clarity. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

groups (Table II), with no significant difference between the clinical groups.

Figure 3 plots w_{m3} against w_{m2} , with the three subject groups distinguished by colour. Points for seven representative subjects are plotted in the w_{m2}/w_{m3} 'weight plane' in Fig. 4, with confidence bounds. In each case, the ellipsoidal outer bound is the locus of weights where the likelihood of the weighted \mathbf{X}_m predicting the observed responses falls to 0.01 of its maximised value [i.e. $LL(\mathbf{X}_m)$ is lower by log(0.01) = -4.6], while the likelihood at the inner bound is 0.05 of its maximized value $[LL(\mathbf{X}_m)$ is lower by -3].

Finally, we found that likelihood was significantly lower across each of the two clinical groups than across

TABLE I. Variance of the coordinates along each dimension of colour space (as a fraction of total variance in that solution) for MDS solutions of the controls (X_{C}), mercury-exposed subjects (X_{Hg}) and diabetes patients (X_{DM-2}).

_	<i>D</i> 1	D2 = D2	desat.)	D3	
X _C X _{Hg}	0.54 0.48	0.28 0.22	0.16 0.14	0.12 0.08	0.16 0.29
X _{DM-2}	0.53	0.23	0.15	0.07	0.25

the control group (Table II). This is consistent with global difficulty in colour discrimination in addition to the blueyellow deficiency apparent here. Likelihoods would also be lower if our model of individual differences simply was not valid for the Hg and DM-2 groups; that is these subjects' responses could be highly discriminant, and consistent with colour spaces derived from X_0 , but through some other transformation. However, this interpretation is not compatible with Fig. 1.

As an afterthought we applied a more conventional weighted Euclidean model of individual variation, varying the parameters w_{m2} and w_{m3} , but applying the former to all stimuli (saturated as well as desaturated). Mean values for w_{m2} did not differ so much between groups: 0.98, 0.91 and 0.90, for the controls, Hg and DM-2, respectively. The difference between w_{m2} values for the controls and the combined clinical groups no longer quite reached significance (P=0.063). However, mean likelihood values were lower for this model than for the desaturation-specific model, causing us to prefer the latter.

DISCUSSION

Previous MDS analyses of these data^{14,15} considered each observer's responses separately, and focussed on the five D-15 and 10 D-15d caps used in the combined assortment, omitting the other 15 caps that each observer only sorted once. Even so, the sparse nature of the data limited

them to two-dimensional solutions. In contrast, the exploratory phase of this analysis could sustain three-dimensional solutions because responses were pooled for each group. This in turn enabled us to observe differences in dimensional-salience parameters.

The D-15 and D-15d tests of colour vision deficiency use colour samples that are spaced at roughly equal intervals around the hue circle and, within each test, do not vary in lightness or saturation. As normally administered, they do not probe the salience of lightness differences to a subject or test for saturation-dependent impairments. Combining the sample sets, as in this study, introduces variations along these two achromatic characteristics (cf. Ref. 51).

The results suggest that in the two clinical groups, the signal along the S_0 or tritan system is greatly decreased for a stimulus containing a small component of blueness or yellowness, leaving the redness or greenness of the stimulus to dominate stimulus appearance and distorting its dissimilarities from other stimuli. Thus, in the MDS solution, the desaturated stimuli collapse towards the R/G axis. Conversely, the dissimilarities perceived among the saturated stimuli are comparable to those for the controls, implying that sufficiently large blue or yellow components can still be detected and produce a normal S_0 signal.

A possible explanation is that mercury exposure and DM-2 impair the detection sensitivity of the S_0 mechanism of colour vision. Blue-yellow sensitivity loss has indeed been reported in the case of mercury intoxication.^{21,23} The decreased S_0 sensitivity is conceivably followed by a compensatory amplification along the blue-yellow system, but only if the original signal is large enough to rise above the threshold of noise.¹⁶

Köllner's rule states that an acquired blue-yellow deficiency can be traced to damage to the retina.⁵² Note though that mercury can affect the visual system in numerous ways, also impacting on the optic nerve and visual cortex.^{26,27}

One cannot expect either of the clinical groups to be homogeneous, given the large variations in the factors



FIG. 2. Distributions of dimensional-weight parameters fitted to data from individual subjects in the three groups (controls, Hg-exposed and DM-2 patients): w_{m2} , salience of differences along the blue-yellow dimension, D2 (left), and w_{m3} , salience of differences along the lightness dimension, D3 (right).

TABLE II. Means and standard errors for dimension-weight parameters w_{m2} , w_{m3} and normalized likelihoodper comparison $I_m = \exp(\text{LL}(\mathbf{X}_m)/140)$ within each group, when \mathbf{X}_0 is adjusted to each subject's responses (left-hand columns). Probability (*t*-value) of pairwise differences between the groups (right-hand columns).

		Mean (SE)			P (t)		
	Controls	Hg	DM-2	C:clinical	C:Hg	C:DM-2	
W _{m2} W _{m3} I _m	1.08 (0.07) 1.02 (0.10) 0.734 (0.024)	0.91 (0.09) 1.56 (0.08) 0.644 (0.018)	0.76 (0.06) 1.41 (0.06) 0.623 (0.021)	0.004 (3.04) 0.000 (-4.39) 0.003 (3.05)	n.s. (1.52) 0.000 (-4.30) 0.005 (2.94)	0.001 (3.53) 0.000 (-3.80) 0.005 (2.91)	

These dimensional parameters are not measured in absolute terms, only relative to $w_{m1}=1$ for all observers.

contributing to their acquired colour vision deficiency, that is length and dosage of mercury exposure and the progressive nature of DM-2. Indeed, the MDS approach reveals considerable variation in the Hg-exposed and DM-2 groups: despite their tendency as groups toward lower w_{m2} , some fell within the distribution of control observers and some departed from the controls in the opposite direction, towards insensitivity to red-green differences (Figs. 2 and 3). Thus, estimating the weights of colour-space axes is not on its own sufficient to unambiguously diagnose the stage of diabetes progression or the impact of mercury exposure. However, the tendency is a reminder of the importance of examining colour vision function when either condition is suspected.

Several studies of mercury-exposed populations that used the CCT to quantify chromatic discrimination thresholds directly along protan, deutan and tritan confusion lines^{24,25,28,32} all found a general, diffuse loss of sensitivity, rather than increased thresholds confined to a specific axis. Note though that in these studies the threshold measurements were averaged across subjects—who were affected to various degrees and may have suffered from different forms of colour vision deficiency.

Clinical group subjects were tested twice, with left and right eye. The correlations between calculated left-eye and right-eye parameters are significant (at P=0.003 or less): 0.391 for w_{m2} , 0.558 for w_{m3} , and 0.566 for likelihood l_m . Some of the differences may be real, as visual impairment from mercury exposure or diabetes need not





FIG. 3. Scatterplot of dimensional-weight parameters w_{m2} and w_{m3} fitted to individual subjects' data. Points colour-coded to distinguish controls, mercury (Hg)-exposed subjects and diabetes (DM-2) patients.

FIG. 4. Parameters w_{m2} and w_{m3} for seven representative subjects (two from control, two from Hg and three from DM-2 groups, points coloured as in Fig. 3), each surrounded by 95% and 99% confidence boundaries (darker and lighter ellipsoids).

affect both eyes with equal severity.²⁹ However, the confidence bounds around these dimensional weights (Fig. 4) indicate that 70 triads are not enough to confine their values very closely, reducing the test–retest reliability of the MDS analysis.

The higher mean w_{m3} in the two clinical groups may indicate a form of compensation for less reliable chromatic discrimination, with these subjects placing more weight on lightness cues as a criterion for making oddone-out judgements. The high correlation between w_{m3} for left-eye and right-eye observations suggests that the increase is central rather than peripheral in nature, for example binocular interaction and/or attentional factors. Notably, Stalmeier and de Weert, using the complete method of triads, found that the salience of lightness was modulated by selective attention.⁵³ Increased weight of the lightness dimension was also found for congenitally colour abnormal observers.^{49,50,54}

This 'compensatory' explanation leaves open a second possibility: the fact is that w_{m3} is not measured in absolute terms, but only relative to the weight placed on the first, R/G dimension; hence any condition that impairs red-green discrimination without affecting lightness discrimination necessarily increases the relative weight of the latter.

Finally, the significantly lower likelihoods l_m for colour spaces of subjects in the clinical groups (Table II) deserve further comment. Specifically, if the affected subjects viewed colour differences in the distorted way modelled here, that is decreased distances along the Blue-Yellow axis for desaturated stimuli, but made odd-one-out judgements that were reliable in those distorted terms, their l_m values would be no lower than those of the controls. The observed low values of l_m indicate that clinical group subjects were in fact responding less reliably, that is their colour discrimination was generally poorer.

This approach may be sensitive to conditions such as complex dyschromatopsia, which the conventional D-15d appears to underestimate.⁵⁵ The analysis is equally applicable to data elicited with other tasks, for instance pairwise numerical scaling. The method of triads has advantages, although, including the relative simplicity of the judgements required of the subject,⁵⁶ and the simplicity of maximum-likelihood (MLE) when the data take the form of dissimilarity comparisons.⁴⁶ The use of randomised triads rather than a standardised list introduces some variation among subjects. Future research in this direction could use a standard, predetermined list of triads; for instance, a 'balanced incomplete design' with λ =2 where each pair of stimuli appears twice.⁵⁶

We have noted that MLE provides an objective test for choosing between alternative explanatory models, the likelihood ratio test. This is suitable for comparing nested models where one model's parameters are a subset of the other's. Another test, the Akaike information criterion, is available for comparing likelihood values between nonnested models.⁴⁶ A further advantage of the MLE approach is the ease with which confidence bounds can be found around parameters when fitting models to individuals or groups to summarise their data.

The resulting data can capture subtle but distinctive patterns of colour-vision impairment when analyzed with individual-differences MDS. There are potential applications as a diagnostic tool—assuming that more triads are collected—and for monitoring the status of an acquired condition. A mixed stimulus set was used, with two values of lightness and saturation, because the dimensions of colour space spanned by the stimuli define the forms of impairment and compensation detectable in this way. A realistic model of individual difference is a second requirement. The model introduced here—that posits impaired discrimination restricted to unsaturated colours—is more in keeping with clinical reports than the usual weighted-Euclidean model, and appears to be a better fit to the data.

APPENDIX

MAXIMUM-LIKELIHOOD ESTIMATION MDS

When a subject chooses cap A as the odd-one-out of the triad {A,B,C}, this is tantamount to ranking the cap pair (B,C) as more similar than the two other pairs (A,B) and (A,C). Writing 'diss(A,B)' for the subjective dissimilarity between A and B, this in turn can be considered as a pair of dissimilarity comparisons: diss(A,B)>diss(B,C), diss(A,C)>diss(B,C), at the time of the decision. It is convenient to express this in a shorthand form: AB » BC, AC » BC.

MDS postulates that diss(A,B) can be modeled by the distance d_{AB} in a low-dimensional space. Specifically, we assume without loss of generality that diss(A,B)= $d_{AB}+e(0)$, where e(0) is a random error term with a mean of 0. If the subject were infallible, so e(0)=0, his or her choices would follow a step probability function of the difference between distances $\Delta(AB,BC)=d_{AB}-d_{BC}$:

$$pr\left(AB \gg BC\right) = \begin{cases} 1 \text{ if } \Delta(AB, BC) > 0\\ 0.5 \text{ if } \Delta(AB, BC) = 0\\ 0 \text{ if } \Delta(AB, BC) < 0. \end{cases}$$

In practice, of course, subjects are fallible-or rather, they are inconsistent, with the perception of any dissimilarity changing from one comparison to another-and although the probability approaches 0 or 1 if $\Delta(AB,BC)$ is sufficiently negative or positive, the transition between them is a smooth ogive. Following Thurstone's model of pairwise comparison, we assume that the error contributions are normal in form. Then pr(AB » BC| $\Delta(AB,BC) = \Phi (\beta \Delta(AB,BC))$, where the cumulative density function $\Phi(x)$ is the integral of the normal distribution and the parameter β is the observer's 'discriminance', higher values denoting a more discerning, consistent set of judgements.

The likelihood that a given combination of interpoint distances in a spatial model would have produced the

observed list of dissimilarity comparisons from a given subject—or from a group of subjects being analyzed together—is the product of all the corresponding probabilities. In this case, there are 140 comparisons per subject (two from each triad), ranking the 435 dissimilarities among the 30 stimuli. Their product is a goodness-of-fit function, with maximum-likelihood estimation working to maximise this combined likelihood by finding the optimum values of parameters.

It is convenient to work with the logarithm of the likelihood, so as to replace the product with a sum of terms:

LL =log likelihood =
$$\Sigma \log (\Phi(\beta \Delta(AB, BC)))$$
.

A version of this, normalized over the subject's 140 comparisons, is $l_m = \exp(\text{LL}/140)$.

For comparison, the older MDS programs MINITRI⁵⁷ and TRISOSCAL⁵⁸ use a least-squares algorithm that defines and minimizes a 'badness-of-fit' Stress function. Each comparison of the form AB » BC contributes a quadratic term $(d_{AB}-d_{BC})^2$ to Stress if $d_{AB}< d_{BC}$, or 0 if the model agrees with the data $(d_{AB}>d_{BC})$. It is worth noting that for sufficiently large discriminance β , the MLE and least-squares algorithms become equivalent (i.e. the former includes the latter as a special case), due to the nature of the log($\Phi(x)$) function, which becomes quadratic for large negative values of x while levelling off at 0 for large positive x.

In one of these analyses, the parameters are the coordinates x_{ip} locating 30 points in three-dimensional space $(1 \le i \le 30, 1 \le p \le 3)$, which can be written as a 30-by-3 matrix X. MTRIAD follows a hill-climbing strategy. The coordinates are optimized through a series of iterations X, X', X''..., in a process analogous to the two-dimensional case of climbing a hill, by finding the direction at each X' in which the slope is steepest (i.e. in which LL(X) increases most rapidly) and taking a step in that direction.

For this, the partial differential of likelihood for each interpoint distance $\partial LL(X)/\partial d_{ij}$ is calculated: for every comparison in the data between that pair of stimuli and another pair, there is a contribution of the form $\partial \log(\Phi(\beta (d_{ij}-d_{jk})))/\partial d_{ij}$. These differentials $\partial LL(X)/\partial d_{ij}$ are converted into partial differentials for each coordinate, $\partial LL(X)/\partial x_{ip}$. The hill-climbing strategy is also common in least-squares implementations of MDS, although the individual contributions are simpler. Constraints among the coordinates are easily incorporated in this process.

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