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Multidimensional Scaling reveals a color dimension unique to 'color deficient' observers

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Introduction

Normal color vision depends on the relative rates at which photons are absorbed in three types of retinal cones, which have peak sensitivities in different regions of the spectrum. The short-wave (S), middle-wave (M) and long-wave (L) cones are maximally sensitive near 430, 530 and 560 nm respectively. However, some 6% of men exhibit a variant form of color vision called deuteranomaly. Their color vision is thought to depend on short-wave cones (S) and two forms of long-wave cone (L, L') [1-3]. The two types of long-wave cone contain photopigments that both peak in the same part of the spectrum, near 560 nm, but their spectral sensitivities are different enough that the ratio of their activations gives a useful chromatic signal. Like color-normal observers, deuteranomalous observers are formally trichromatic, in that they require three primary lights if they are to match all possible spectral power distributions in a color-matching experiment, but the matches they make are different from those of the normal. Deuteranomaly is rare in women, since the genes that encode the middle- and long-wave pigments are on the X-chromosome [2] and thus a woman must inherit two anomalous chromosomes if she is to exhibit deuteranomaly.

The subjective world of the deuteranomalous trichromat has been little explored. The technique of Multidimensional Scaling (MDS) has previously been used to reconstruct subjective color spaces from observers' judgements of the similarities of individual pairs of colors [4-7]. The input to the scaling program is a matrix representing the similarities of all possible pairs in the set of stimuli; and the output is a map of the stimulus set that minimizes the differences between the input proximities and the corresponding proximities in the derived space. The length of the vector between any two stimuli in the output space indicates how similar they appeared to the subject, while its direction may allow the experimenter to interpret the dimensions that guided the subject's judgement. MDS has been applied to the case of anomalous trichromats and their subjective spaces have been found to be contracted compared to those of normals (e.g. [6, 8, 9]).

However, MDS studies of deuteranomaly have always had a phenotypic bias: The stimuli have been selected to be discriminable for the normal observer. Anomalous trichromats are often referred to as 'color deficient', but this term represents the viewpoint of the majority phenotype. Because anomalous observers have a different set of retinal photopigments from normal, there must exist pairs of natural stimuli that appear distinct to the anomalous but are indistinguishable ('metameric') for the normal [10]. In other words, there are distinct spectral power distributions that produce the same triplet of photon catches in the cones of the normal eye but produce distinguishable triplets of photon catches in the eye of the anomalous trichromat.

{figure 1 about here}

In the present study, our stimuli were disks of 40-mm diameter painted with mixtures of single-pigment acrylics. To the normal eye, the stimuli appeared to be desaturated greens, varying along a yellow-blue axis. We included pairs of samples gave spectral power distributions that were near-metamers for normals but were calculated to be distinguishable by a model deuteranomalous observer. Thus there were two distinct subsets within our stimulus set: One, labelled X, was made from mixtures of Cadmium Yellow and Cobalt Blue and the other, labelled Y, contained mixtures of Yellow Oxide and Ultramarine Blue. Figure 1 shows an example of the spectral power distributions of such an X-Y pair under our experimental illuminant.

In selecting suitable stimuli, we modelled the photon catches of individual photoreceptors when exposed to the light reaching the eye from a given stimulus under the experimental illuminant. Using a spectroradiometer at the position of the observer's eye, we measured the spectral power distribution ($E(\lambda)$), and multiplied it in turn by the spectral sensitivities of short-wave, middle-wave and two classes of long-wave cone ($\varphi_{(S)}(\lambda)$, $\varphi_{(M)}(\lambda)$, $\varphi_{(L)}(\lambda)$, and $\varphi_{(L')}(\lambda)$). We used the spectral sensitivities for normal and deuteranomalous cones given by DeMarco et al. [11]. Integrating each product between 400 and 700 nm gave the photon catches in the four classes of cone. The possible chromatic signals available to a normal and to a deuteranomalous observer were then modelled as ratios of cone activations, e.g. $(\int \varphi_{(M)}(\lambda).E(\lambda) \delta\lambda) / (\int \varphi_{(L)}(\lambda).E(\lambda) \delta\lambda)$. Hereafter, we refer to photon catch ratios of this kind as M/L etc. The 15 stimuli chosen for the final set included pairs that were calculated to vary in the unique dimension of the model deuteranomalous observer, corresponding to the ratio L'/L , but were near-matches in the normal dimensions of luminance ($L+M$) and chromaticity ($S/(L+M)$ and M/L). In the right-hand plot of Figure 2 we show the positions of the stimulus set in the MacLeod-Boynton chromaticity diagram [12] for normal color vision: Note that the samples predominantly fall along a single line and that X and Y stimuli are intermingled. In the left-hand plot of Figure 2 we show the stimulus set in an analogous diagram constructed for the deuteranomalous observer: Note that there is a clear separation of the X and Y subsets.

{figure 2 about here}

The fifteen stimuli were presented pair-wise under a broad-band amber illuminant, intended to minimise variation of the stimulus set in the S-cone chromatic dimension, which is shared by both normals and deuteranomalous observers. Subjects were asked to rate the color difference between each pair on a scale of 0 to 10 and their ratings were recorded in a matrix of subjective dissimilarity judgements. Non-metric MDS was used to reconstruct a subjective color-space from the matrix of dissimilarity judgements for each observer.

Results

The left-hand panels of Figure 3 show two-dimensional MDS solutions for individual deuteranomalous observers, while the right-hand panels show two-dimensional solutions for individual normal observers. The left-hand panels reveal a subjective color dimension unique to the deuteranomalous: The first dimension for each of these observers shows a clear separation of the x and y stimulus subsets, a separation that is not present in the normals' spaces. For a color-normal experimenter, it was striking to watch a deuteranomalous subject giving large difference ratings to apparently identical stimuli, and doing so without hesitation.

For each observer, we correlated the ranks of the stimuli along the modelled dimensions with the ranks along the subjective dimensions revealed by MDS for that observer. For the three deuteranomalous subjects shown in Figure 3, the first MDS dimension correlated significantly with L'/L ($0.821 \leq r_s \leq 0.950$) and the second dimension correlated significantly with S/(L'+L) ($0.700 \leq r_s \leq 0.957$). Moreover, the ranks of the stimuli along the subjective first dimension correlated between subjects ($0.764 \leq r_s \leq 0.971$), as did the ranks along the second dimension ($0.686 \leq r_s \leq 0.907$). Thus for these three subjects the derived space appears to be truly two-dimensional, with axes corresponding to the theoretical axes in the left-hand panel of Figure 2. A fourth deuteranomalous observer was tested and gave an essentially one-dimensional solution: This dimension correlated highly with L'/L ($r_s = 0.964$) and with the first dimension for the other deuteranomalous observers ($0.818 \leq r_s \leq 0.964$).

In contrast to the deuteranomalous subjects, for all the normal observers, the first dimension of the MDS solution correlated with S/(L+M) ($0.875 \leq r_s \leq 0.964$) and with L/M ($0.868 \leq r_s \leq 0.964$), as would be expected from Figure 2 (right-hand panel). There was no significant correlation of the ranks of the stimuli along their second dimensions with any dimension modelled. We also correlated the ranks of the stimuli along subjective dimensions between observers. The ranks of the stimuli along all normal observers' first dimensions correlated significantly ($0.854 \leq r_s \leq 0.993$), whereas there was no correlation of the ranks of the stimuli along the second dimension between normal observers. Two control subjects took the test twice and the ranks of the stimuli along their subjective first dimensions were significantly correlated across tests ($r_s = 0.946, 0.943$), but there was no significant correlation for the second dimension.

In summary, when a two-dimensional solution is imposed on the normal's matrix of dissimilarity ratings, one consistent axis emerges, as would be expected from figure 2b, but the second axis is not consistent and probably represents only noise.

{Figure 3 about here}

Conclusions

In previous studies of the subjective world of the anomalous trichromat, experimenters have adopted the bias of the majority phenotype and have concluded that the deuteranomalous colour space is compressed relative to that of normals. Indeed, deuteranomalous observers are commonly categorised as 'color deficient'. Yet when suitable stimuli are used, it is possible to see an *expansion* of deuteranomalous color space relative to the normal space. The deuteranomalous observer is trichromatic, but his trichromacy is a different one from that of the normal. The spectral power distributions of a pair of stimuli can differ physically but yield the same, or nearly the same, triplet of photon absorptions in the three normal cones; and yet these spectra may differ in the triplet of photon absorptions they yield in the cones of a deuteranomalous observer. In addition, it is possible that a post-receptoral gain amplifies the deuteranomalous L'/L signal so that neurally it occupies the same dynamic range as the L/M signal of the normal trichromat [13].

The advantage enjoyed by anomalous trichromats in our test may have a real-world counterpart in the discrimination of natural spectra that are metamers for normal observers. It is possible that this advantage has maintained the minority anomalous genotype in the population. A recurrent idea – though one without experimental support – has been that anomalous trichromats are able to penetrate military camouflage if the camouflage paints are

metamers of the natural foliage or terrain that is being simulated [14-16]. In the natural world it is possible that the minority phenotype has been able to spot predators or food sources that are less visible to the majority phenotype. Analogues of both normal and anomalous forms of human vision are found in the platyrrhine primate, *Cebus apella*, and Regan et al [17] have calculated that some fruits in the *Cebus* diet are more visible against foliage to the deuteranomalous phenotype and other fruits more visible to the protanomalous phenotype, with the 'normal' phenotype being intermediate.

It remains to be seen whether the L'/L dimension, so visible to our deuteranomalous observers, is also accessible to female carriers of deuteranomalous vision. Owing to X-chromosome inactivation [18, 19] such heterozygotes will express four types of cone in their retina (e.g. S, M, L, L'). If the independent L'/L signal is preserved as far as the cortex, such women may have a heterozygous advantage: They may have access to a color dimension additional to those available to normal trichromats, and may therefore be tetrachromatic [20]. If such tetrachromats do exist, our test may be able to reveal them.

Experimental Procedures

In order to create stimuli that were near-metamers for normal trichromats, mixtures of single-pigment paints were used, in a strategy similar to that of Maximov and Derim-Oglu [21], who used mixtures of mineral paints to show that hollow-dwelling passerine birds can discriminate human metamers. There were two distinct subsets within our stimulus set. One, labelled X was made from mixtures of Cadmium Yellow (Liquitex, PY35) and Cobalt Blue (Liquitex, oxides of cobalt and aluminium, PB28), and the other, labelled Y contained mixtures of Yellow Oxide (Liquitex, synthetic hydrated iron oxide, PY42) and Ultramarine Blue (Windsor and Newton, complex aluminosilicate containing sulphur, PB29). These surfaces were selected from a much larger set on the basis of their energy spectra, measured with a PhotoResearch PR650 spectroradiometer under an amber illuminant with CIE chromaticity co-ordinates $x = 0.47$, $y = 0.46$. Using the cone fundamentals of DeMarco et al (1992), we modelled the effects of the stimulus spectra on normal and anomalous cones (i.e. L, M, S – and L', the second long-wave cone of the deuteranomal). We chose the final set of stimuli to include pairs for which (i) the signals (L+M), M/L and S/(L+M) differed by less than 1%, whereas (ii) the private signal of the deuteranomal, L'/L differed by more than 1%.

The painted surfaces were made into fifteen discs of 40mm diameter set in black rims for presentation and handling. Every possible pair of stimuli was presented to subjects against a black ground, and subjects were asked to rate on a scale of 0 to 10 how different the pair appeared in hue. A preliminary series of at least 20 presentations allowed subjects to set up their internal scale and allowed their consistency to be monitored before data collection began.

Subjects were 4 male and 3 female normal controls aged 17-60, and 3 male and 1 female deuteranomalous trichromats, as classified by the Oculus anomaloscope, aged 21-54. The deuteranomals had anomaloscope matching ranges of between 0.3 and 4.7 Nagel units [22] and the normals of between 1.0 and 5.1 units.

The primary result of the experiment was a matrix of similarity judgements for each observer. A non-metric multidimensional scaling program [4] was used to construct a subjective space from each matrix. These reconstructed spaces, which were rotated for interpretability of axes, showed a best-fit map of the subjective proximities of the stimuli relative to each other. We were then able to correlate the ranks of the stimuli along

subjective dimensions with their ranks along the modeled dimensions, using Spearman's rank correlation.

Figure 1) The spectral power distributions of a pair of our stimuli that are near-metamers for the normal trichromat.

Figure 2) Positions of the chromaticities of the 15 stimuli in MacLeod-Boynton space for the normal observer (right) and in an equivalent space for the deuteranomalous observer (left). The X (•) and Y (◦) stimulus subsets are separated on the deuteranomalous dimension $L'/(L'+L)$ (left) but intermingled on the normal dimension $L/(L+M)$ (right).

Figure 3) MDS two-dimensional reconstructed proximity maps of the stimuli for three deuteranomalous observers (left) and three normal observers (right). The deuteranomalous space shows a separation of the X (•) and Y (◦) stimulus subsets, while the normal space does not.

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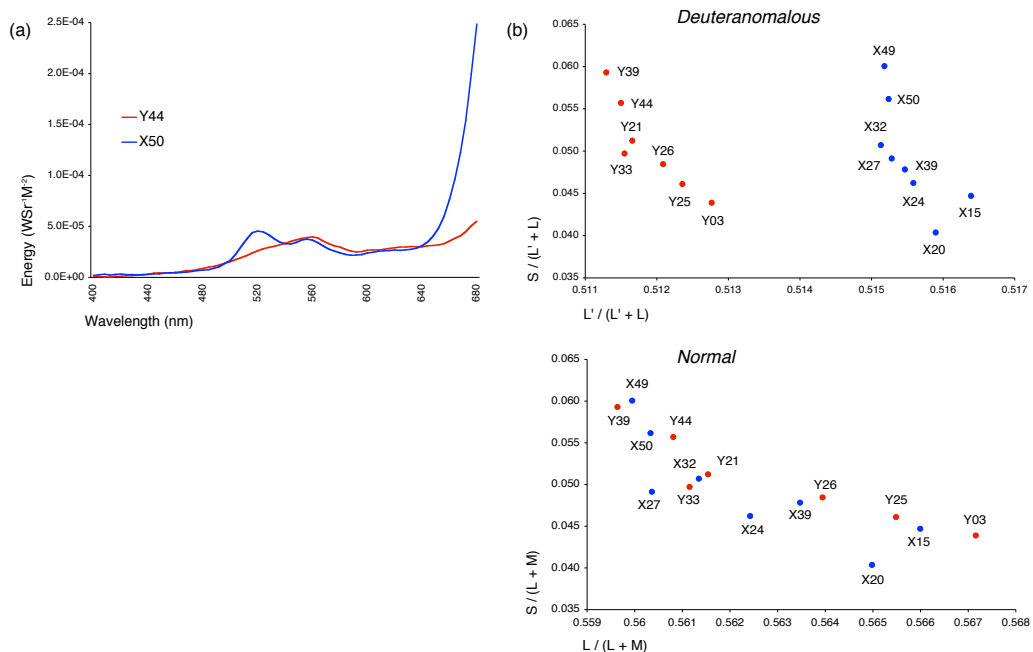


Figure 1. Experimental stimuli.

(A) Spectral power distributions of a pair of our stimuli that are near-metamers for the normal trichromat. (B) Positions of the chromaticities of the 15 stimuli in MacLeod-Boynton space for the normal observer (below) and in an equivalent space for the deuteranomalous observer (above). The X (blue points) and Y (red points) stimulus subsets are separated on the deuteranomalous dimension $L'/(L'+L)$, but intermingled on the normal dimension $L/(L+M)$.

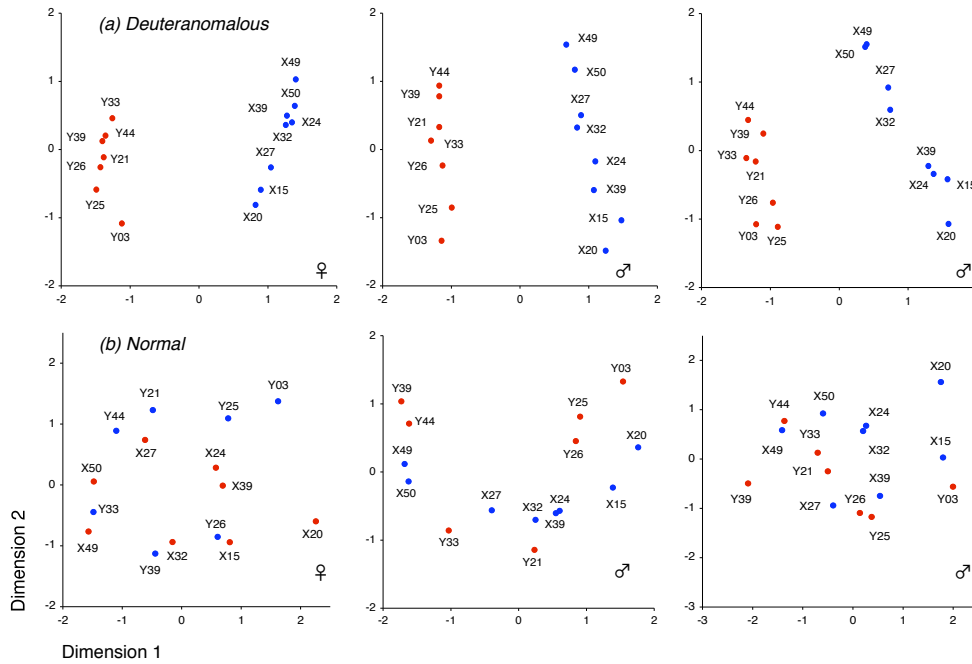


Figure 2. MDS two-dimensional proximity maps of the stimuli for three deuteranomalous observers (A) and three normal observers (B).

The spaces have been rotated to allow interpretation of axes. The deuteranomalous spaces show a firm separation of the X (blue points) and Y (red points) stimulus subsets, while the normal spaces do not. The two male and one female deuteranomalous subjects (ages 21–54) were identified with an Oculus anomaloscope and had matching ranges of 0.3–4.7 Nagel units [1]. Our total of four male and three female normal observers (aged 17–60) had matching ranges of 1.0–5.1 units.