45. Constructing the color space of the deuteranomalous observer

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Abstract

The discriminability of 66 pairs of colors was quantified by measuring the time that observers needed to judge whether the two colors in each pair were the same or different. A multidimensional scaling procedure was used to order the colors in a space such that the distance between colors was inversely related to the response time that they produced: i.e., more discriminable colors were plotted farther apart. The resulting color spaces of two deuteranomalous trichromats are markedly different from that of a normal observer and suggest an impoverished color world.

Introduction

Whereas the color matching functions of anomalous trichromats have been studied in some detail (Nelson, 1938; Alpern and Moeller, 1977; Wolf and Scheibner, 1982), we know remarkably little about the structure of the subjective color space of such observers. In a pioneering study, Helm (1964) used ratio judgments of similarity to construct uniform color spaces for two color-deficient observers, but his subjects were classified only loosely by performance on the H-R-R plates. Yet there is both theoretical and practical significance in knowing how the perceptual gamut is contracted or distorted in particular forms of anomalous trichromacy; we have therefore used a performance measure of color discrimination to study the differences between the color spaces of normal and anomalous observers. While the results in the present paper refer to deuteranomalous vision, the method is applicable to other types of color deficiency.

It has been argued elsewhere (Mollon and Cavonius, 1986) that uniform color spaces cannot be validly constructed by counting the number of just-noticeable-differences that lie along a path between two chromaticities. Instead for our purpose we require a method that directly estimates the discriminability of colors that are perceptually quite different. A time-

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honoured measure of the discriminability of two stimuli is the time that one needs to judge that they are different (Henmon, 1906). We therefore presented pairs of colors and measured how long an observer took to decide whether the two colors in each pair were the same or different. Any pairs of different colors that yielded the same response times were defined as equally discriminable, whereas colors that were more quickly discriminated were taken to be more easily discriminable, and colors that took longer to discriminate were taken to be less discriminable. By means of a multidimensional scaling program, the matrix of reaction times was transformed to yield a space in which the separation of colors was a function of their discriminability.

Methods

The observers fixated a dim cross on a dark screen. At the beginning of each trial two 15 $cd.m^{-2}$ patches of color appeared, one on either side of the cross. The patches were $2 \times 2°$ squares, the inner edges of which were 1° from the cross. In half of the trials the patches differed in chromaticity, and in the other half both patches were of the same chromaticity; the two conditions were randomly intermixed. The subject was required to press one key when the colors were the same and another key when they were different; the response caused the colored squares to disappear and terminated the trial. If an error was made, the subject was notified by a tone, and the trial was discarded in the subsequent analysis. Only the responses to 'Different' trials were used in the analysis: the 'Same' trials were presented only to require the subject to make a discrimination. In the course of several experimental sessions, each possible pair of colors was presented 60 times.

The set of chromaticities used is shown in Fig. 1. In Fig. 2 these chromaticities are replotted in the conventional CIE u', v' uniform chromaticity space.

In order to derive a color space from the reaction times, we wished to plot close together those pairs of colors that yield long reaction times (because a long reaction time implies that they are difficult to discriminate). Similarly, pairs that yield short reaction times belong far apart; and intermediate values should be separated in the color space by distances that are inversely related to the reaction times that they produce. In order to avoid any assumptions about the shape of the function that relates reaction time to discriminability, only the rank-ordering of the reaction times was used. To construct the desired space, we used a multidimensional scaling (MDS) program. Such programs have commonly been used to construct perceptual spaces from subjective ratings of stimulus differences (e.g. Indow, 1988), but MDS programs are formally independent of how the estimates of psychological differences are obtained and thus reaction times can legitimately be substituted for subjective ratings (Shepard, Kilpatrick and Cunningham, 1975).

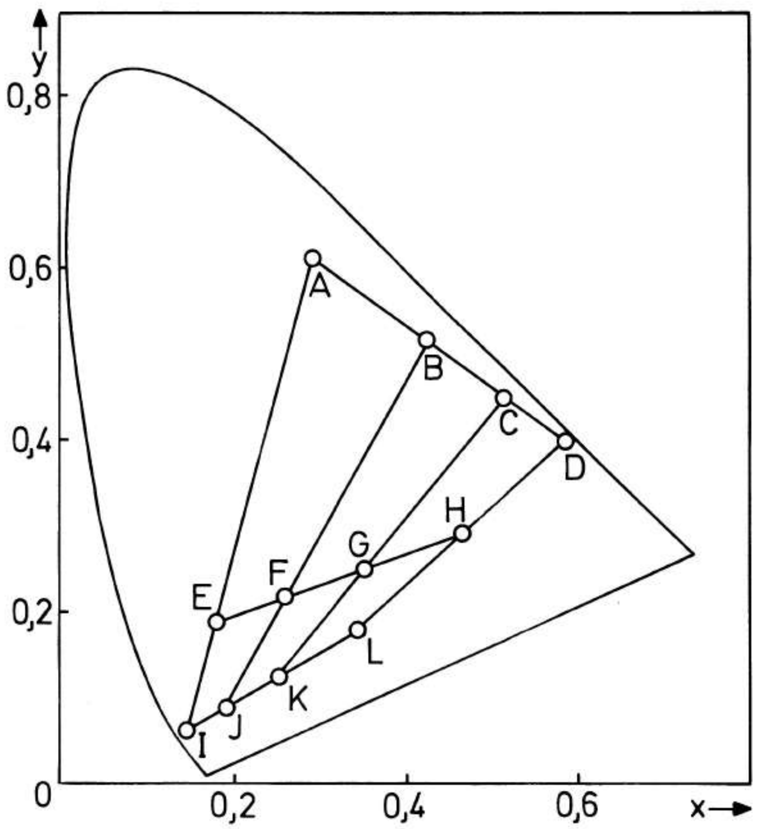

Fig. 1. Locations of the stimulus chromaticities in the CIE *x, y* chromaticity diagram.

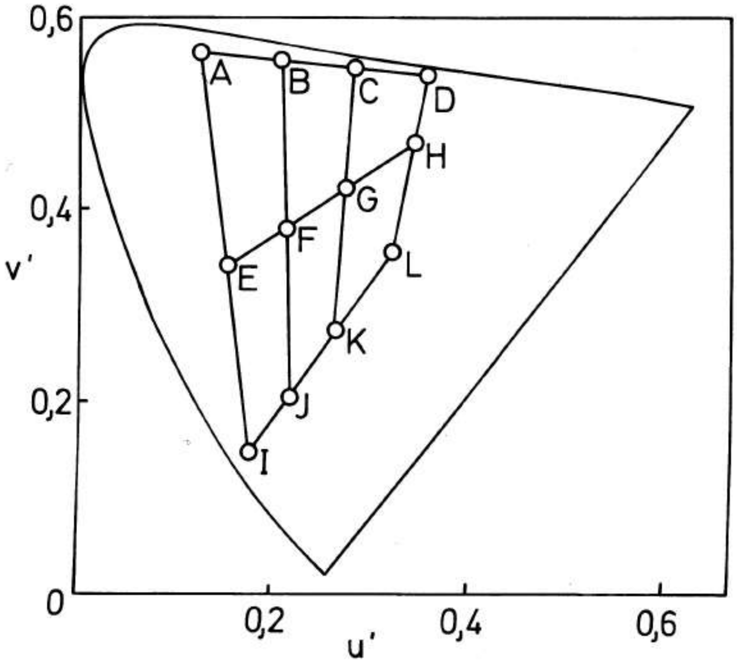

Fig. 2. Locations of the stimulus chromaticities in the u', v' uniform color diagram.

The specific program used here was KYST (Kruskal, 1964), chosen because it is intended for analyzing the data of individual observers and because it can analyze non-metric (i.e. rank-order) data.

The two deuteranomalous subjects were male students in their mid-twenties. Both had first become aware of their anomalous color vision when tested at the beginning of military service. On the Nagel anomaloscope (Schmidt and Haensch), KB made mixture settings between 17 and 32, with a median of 24.5, and GE made mixture settings between 15 and 27, with a median of 18.5. Farnsworth-Munsell results for these two subjects are shown in Fig. 3. One of the authors (CRC) served as a color-normal subject.

Results and discussion

The normal color space

By successive approximations we developed a set of chromaticities (those shown in Figs. 1 and 2) which, for a normal observer, result in a 2-dimensional subjective space in which neighboring colors are separated by roughly similar distances. Figure 4 shows the reconstructed perceptual space that corresponds to this set of chromaticities. It closely resembles the space

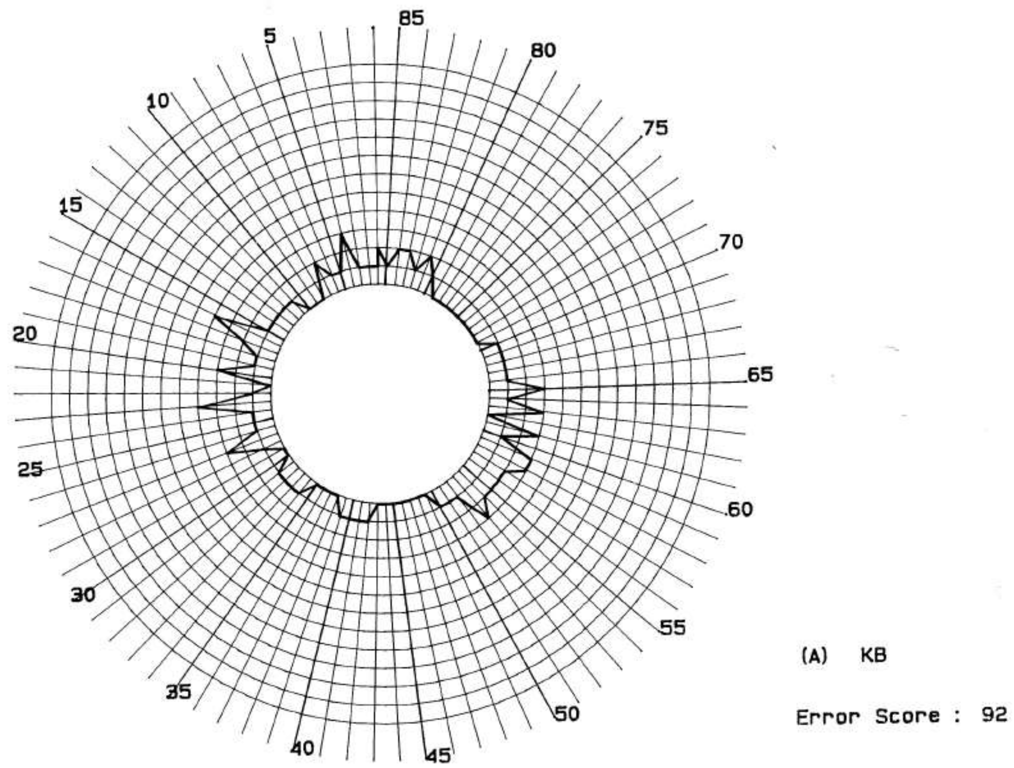

Fig. 3. Farnsworth-Munsell 100-hue results for the anomalous observers KB (left) and GE (right).

generated earlier by the same observer for a slightly larger set of chromaticities (Mollon and Cavonius, 1986). The vertical axis of the reconstructed space corresponds to variation in a tritan direction, and thus to the vertical axis of the chromaticity diagram of MacLeod and Boynton (1980) and to one of the cardinal directions of Krauskopf, Williams and Heeley (1982). But the horizontal axis of our perceptual space does not correspond closely to the second axis identified by MacLeod and Boynton and by Krauskopf *et al.* Note also that distances that are nearly equivalent in Fig. 4 are far from equal in the CIE u', v' uniform color diagram (Fig. 2). An array of stimuli that *are* equally spaced in the u', v' diagram yields a reconstructed color space that is severely compressed in the yellow-violet direction (Mollon and Cavonius, 1986), a result that casts doubt on the general validity of the u', v' diagram as an approximation to a uniform color space.

The deuteranomalous colour space

Figures 5 and 6 show the color spaces reconstructed from the reaction times of the two deuteranomalous observers. These spaces are very different from those of normal observers and, at first glance, may appear anarchic. But the two spaces exhibit a very similar structure, a structure that has a secure theoretical basis: all of the stimulus chromaticities lie approximately along a horseshoe and, with only one transposition (chromaticities L and F in each

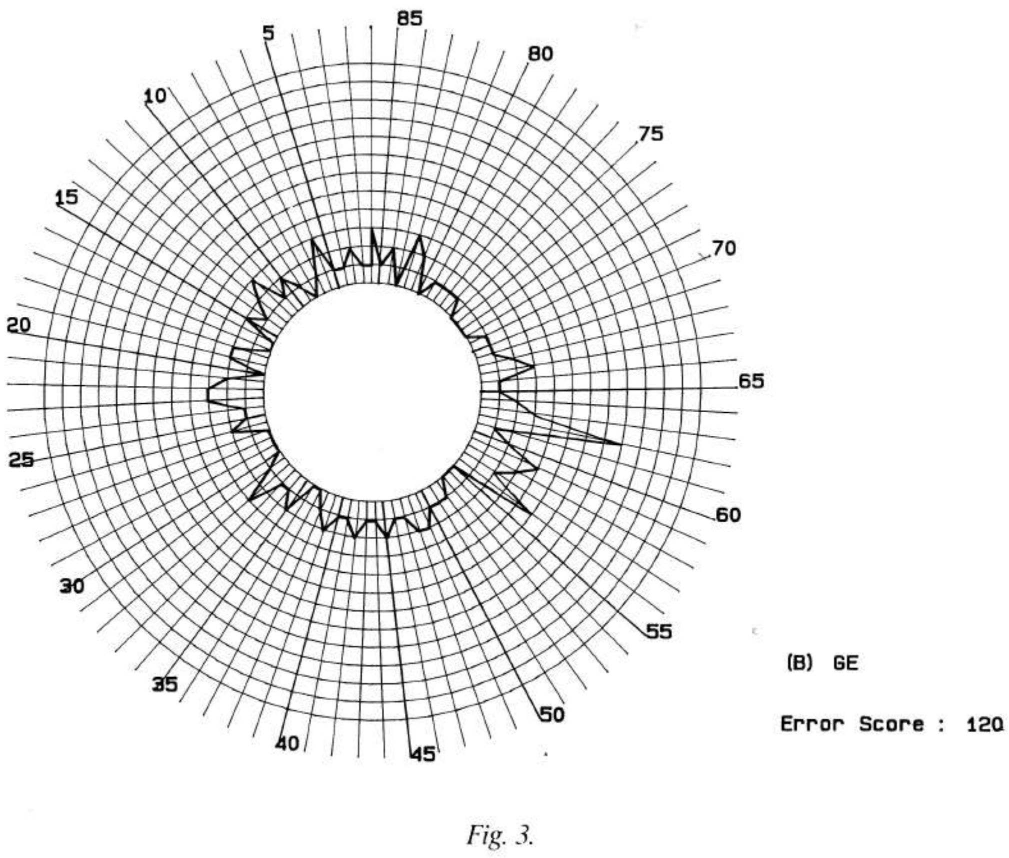

Fig. 3.

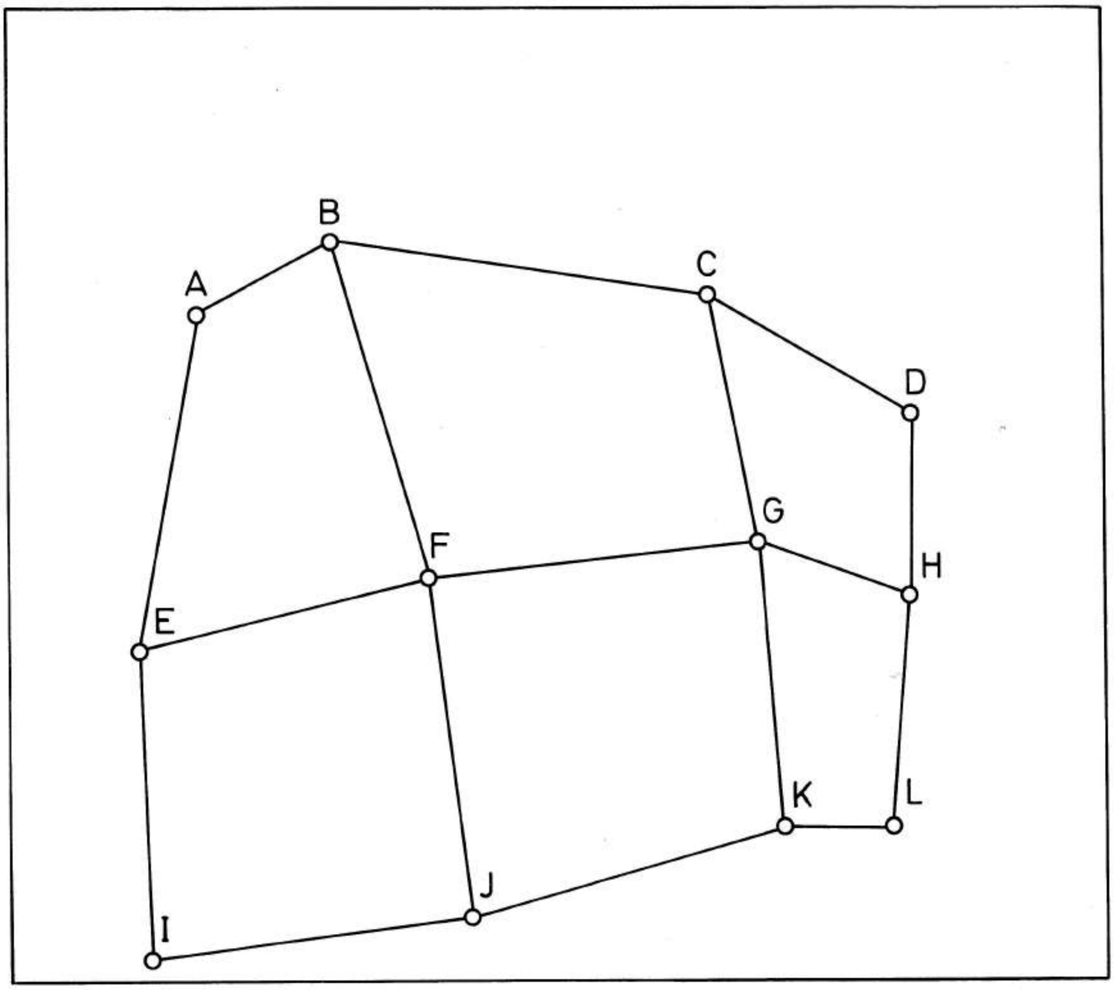

Fig. 4. Color space for a normal trichromat, reconstructed from response times to pairs of chromaticities from Fig. 1.

case), the stimuli are ordered along the horseshoe according to their relative effect upon the short-wavelength cones. Lines that radiate from $x = 1.0$, $y = 0$ in the CIE chromaticity diagram are lines that represent constant excitation of the short-wave cones (Boynton and Kambe, 1980); so the reader can check our interpretation by mentally superimposing such radial lines on the array of chromaticities shown in Fig. 1.

Thus, the internal color space of the deuteranomal appears to be dominated by the signal of the phylogenetically ancient sub-system of primate color vision — the channel that draws opposed inputs from the short-wave cones, on the one hand, and on the other from some combination of signals from the two types of long-wavelength cones (Mollon and Jordan, 1988/1989). In normal observers, variation in this signal corresponds subjectively to changes along the dimension Warm, Neutral, and Cold.

The clustering of the stimuli roughly along a single curve (Figs. 5 and 6) recalls the horseshoe-like locus obtained by Tansley and Boynton (1976, 1978), who asked their observers to give subjective ratings of the distinctness

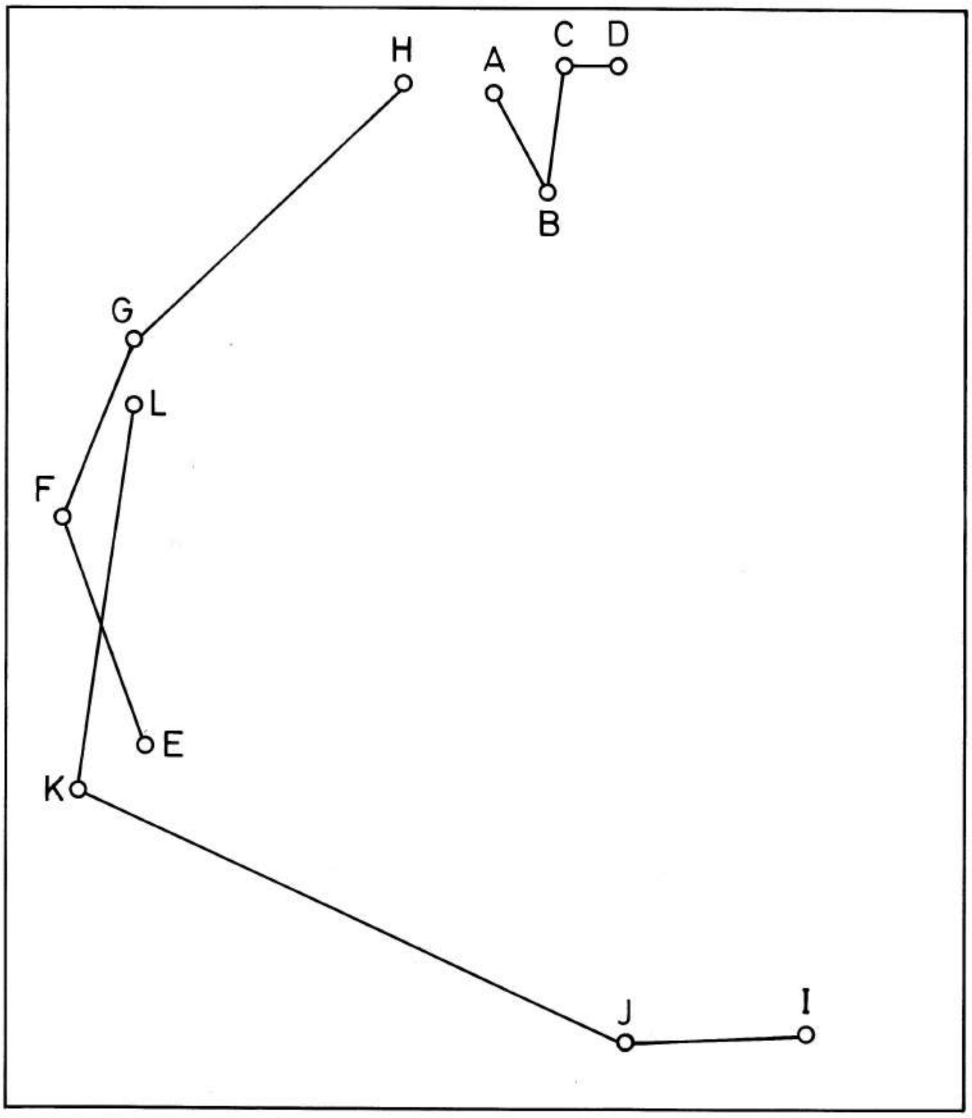

Fig. 5. Color space of deuteranomalous observer KB, reconstructed from the response times to pairs of chromaticities from Fig. 1.

of the border formed by abutting two chromaticities of equal luminance. As in the present analysis of reaction times, the non-metric form of KYST was used by Tansley and Boynton to analyze their matrix of subjective ratings, and the horseshoe-like locus was obtained when the program was allowed a two-dimensional solution. But the difference is that ratings of equiluminant borders by normal observers gave a locus along which the ordering was described by the relative excitation of long- and middle-wave cones, whereas the reaction times of our deuteranomalous observers yield a horseshoe ordered according to the relative excitation of the short-wave cones.

The result obtained for our deuteranomalous observers closely resembles one of the two spaces shown for 'color-deficient' subjects by Helm (1964). The subject 'JN' (Helm's Fig. 5) exhibits a C-shaped solution; and if the chromaticities along the C-shaped locus are replotted in the CIE diagram

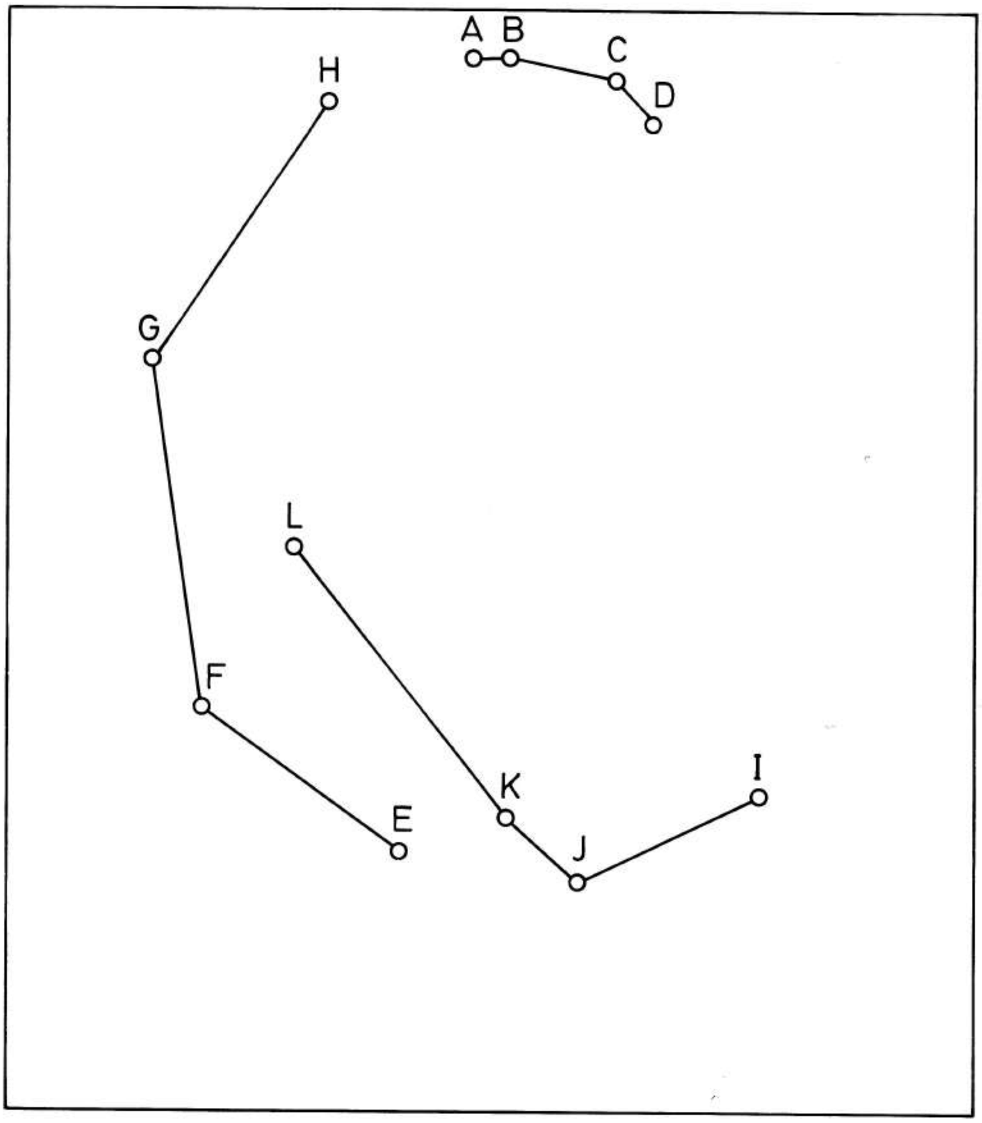

Fig. 6. Color space of deuteranomalous observer GE, reconstructed from the response times to pairs of chromaticities from Fig. 1.

they will be seen to be ordered according to the degree to which they excite the short-wave cones. JN's defect is not explicitly classified by Helm, but it can be inferred from the text that this subject was categorized as 'deuteranomalous' by the H-R-R plates.

Dimensionality of the deuteranomalous space

It is known that multidimensional scaling programs will sometimes generate a horseshoe locus in two dimensions when the subjective space has effectively only a single dimension: if the program is allowed a two-dimensional solution, the derived plot may curve in order merely to account for more of the random variation in the data (Shepard, 1974). This was the objection made by Rodieck (1977) to the analysis of Tansley and Boynton (1976), who originally suggested that two dimensions were required to describe their results.

So do Figs. 5 and 6 imply a deuteranomalous color space that is truly two-dimensional? We might suppose that the space would exhibit a second axis corresponding to a color system that compares the signals of the two types of long-wave cone thought to be present in the deuteranomalous retina. This does not seem to be the case. For we should expect the ratio of excitation of the two long-wave cone types to vary with the relative output of the red phosphor of the display. But moving from left to right in the plots does not correspond systematically to an increase in the output of the red phosphor: the chromaticities ABCD correspond to an increase in this output, but that is also the case for the set IJKL, which exhibit the opposite left-right ordering in the reconstructed space. Notice too that few stimuli depart from the horseshoe to occupy the middle of the space: it is unlikely that there exist real chromaticities that would plot in the center of the space.

Nevertheless, we provisionally and tentatively suggest that the two-dimensional solution of Figs. 5 and 6 does better represent the deuteranomalous color space than does a one-dimensional solution — even though the corresponding variation at a distal level, the degree of excitation of the short-wave cones, is only one-dimensional. In support of this position, we note that a one-dimensional solution orders the chromaticities in a way that is less perfectly related to the excitation of the short-wave cones; and that in the case of GE (Fig. 6) stimulus I is placed closer to D and C than it is to G, a result reflected in the raw reaction times. True horseshoes, whose ends curve inwards, were similarly found for normal observers by Cavonius and Mollon (1984) when they used sets of chromaticities that lay along a single dichromatic confusion line (protan or tritan). To explain such results, we note that a unidimensional physical stimulus may correspond to a perceptual dimension that is bipolar, a dimension of the type that Gibson (1937) called 'oppositional'. The stimuli that lie at opposite ends of such a bipolar dimension may have some phenomenal quality in common (here, saturation) that they do not share with stimuli lying near the equilibrium point of the dimension. Permitted a second dimension, the MDS program shows us the resemblance between the two ends of a single stimulus series.

It is hard to believe that the deuteranomal's perceptual experience contains no component corresponding to the 'red-green' variation of normal experience; but the smallness of any such component is shown by the tight clustering of the stimuli ABCD in Figs. 5 and 6. These are stimuli (Fig. 1) that lie almost on the long-wave spectrum locus.

Conclusions

The most striking aspect of our results is the great difference between the color space of the deuteranomalous observers and that of a normal observer. The deuteranomalous world is dominated by the color system that compares the excitation in short- and long-wave cones. Yet the anomalous observers of the present study exhibit narrow matching ranges on the Nagel anomaloscope and would conventionally be described as 'simple deuteranomalous'. Their Farnsworth-Munsell 100-hue results (Fig. 3) do not show a gross impairment of color discrimination, and it is commonly thought that the perceptual worlds of such observers do not differ much from those of normal observers. Our results suggest that they do.

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