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The discriminability of colours on c.r.t. displays

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SUMMARY

Discriminative reaction times are used to derive a new type of uniform colour space, in which colours that are equally separated are colours that require the same time to be discriminated. It is hoped that the results will guide the system designer in the choice of sets of colours for colour-coding purposes.

1 Introduction

One of the chief criteria for selecting colours for a c.r.t. display must be their discriminability. Regardless of the specific use to which a display is put, colour-coding will be ineffective if the user is not able to discriminate the stimuli rapidly and with a low error rate. Suppose that a colour-coding system is intended to distinguish n states or events. How should the system designer select n colours from the set of all colours in such a way as to maximize discriminability?

To answer this question it would be helpful to have a spatial representation of the set of all colours—or of the subset available on a typical colour raster display—in which colours of equal discriminability were everywhere separated by the same distance. It is important to distinguish such a colour space from a conventional 'chromaticity diagram', such as that of Fig. 1(a). A chromaticity diagram shows the proportion of three primary wavelengths required to match any given light. Such a space is possible because all our sensations of hue depend on just three classes of retinal cone. If two lights of different spectral composition yield the same ratios of photon absorptions in the three classes of cone, and thus require the same proportions of the primary wavelengths for a match, then they will plot at the same position in a chromaticity diagram. But the chromaticity diagram tells us only about matches. It does not tell us how the stimuli look; and it is well established that equal distances in such a diagram do not correspond to equal phenomenological distances.[1]

Closer to what we need are the existing 'uniform colour diagrams', such as the CIE u',v' space of Fig. 1(b); these represent transformations of the chromaticity diagram such that equal distances more nearly correspond to equal phenomenological distances (Ref. 1, Chaps 6 and 9). However, 'uniform colour diagrams' are based on thresholds for discriminating closely similar colours, that is, on data such as the Wright dashes[2] and the MacAdam ellipses.[3]

These threshold data were collected under conditions in which the observer was under no pressure to respond quickly, whereas real-world tasks often require the operator to make rapid discriminations on the basis of colours that differ considerably in hue or saturation. And there are nowadays specific reasons for doubting that the discriminability of large colour differences can be predicted by counting the number of just-noticeable-differences along particular lines in the chromaticity diagram. Consider the colour-differencing channels of the visual system, i.e. the post-receptoral channels which draw inputs of opposite sign from different classes of cone and which provide, almost certainly, the basis for our colour discrimination. There is both physiological and psychophysical evidence that such colour-differencing channels enjoy high sensitivity only over a limited operating range, an operating range that shifts as the state of chromatic adaptation is altered.[4] Thus in the experiments of MacAdam the set-points of the colour-differencing channels would change whenever the experimenter changed the point in chromaticity space on which the measurements were centred. Within the limits imposed by other factors, the point of minimum threshold would follow the experimenter around the chromaticity space. But at any moment the set-point of a colour-differencing channel can correspond to only one point in chromaticity space. And thus, if we wish to estimate the instantaneous difference between two widely separated colours, it may be illegitimate to estimate it from a series of just-noticeable-differences, each obtained in a different state of chromatic adaptation.

An alternative way of constructing a uniform colour space is to collect observers' direct judgements of stimulus dissimilarities (e.g. Ref. 5). But we cannot be certain that the subjective *dissimilarity* of two stimuli is the same as the *discriminability* that would be given by an objective measure of performance; and it is the latter with which the system designer is concerned.

Our solution is to derive our space directly from a performance measure of discriminability: discriminative reaction time. It is known that discriminative reaction time typically decreases monotonically as the physical difference of two stimuli increases.[6,7] In the present case, we operationally define discriminability in terms of the time that colour-normal observers require to decide whether two colours are the same or different. Pairs of colours are presented on a c.r.t. screen, and the observer must respond with different keys according to whether the two colours are the same or different. In the course of an extended, randomized, series of trials, each colour is paired with itself and with each other colour.

From the resulting data we wish to construct a uniform colour space that has an immediate validity for a system designer, a space which is such that colours that are separated by equal distances are colours that require the same number of milliseconds to be discriminated. If a given pair of colours give a longer reaction time, then the members of the pair are to be plotted closer together in the space; and if they give a shorter reaction time, then they are to be plotted further apart in the space. Thus, increasing separation in the space is to mean better discriminability.

To derive such a space from our data we use the non-metric multidimensional scaling program KYST.[8] Programs such as KYST typically take as their input an observer's ratings of the subjective similarities between members of a set of stimuli; but we have substituted objectively-measured reaction times in place of the conventional input. As used here, KYST arranges the colours in a space such that the rank order of the distances between the members of each possible pair of colours is complementary to the rank order of the reaction times associated with each pair. Notice that we assume only a monotonic relationship between reaction time and separation in the space. Notice also that the number of dimensions of the space is not pre-decided. The question of the most appropriate dimensionality is theoretically interesting; but for the practical application of the method, with which we are concerned here, the useful number of dimensions will be the minimum needed to account for most of the variance in the data.

The experiments reported here are preliminary ones; but they clearly show the feasibility of the method and they already suggest that conventional 'uniform colour spaces' do not accurately predict the speed with which colours can be discriminated.

2 Methods

Pairs of colours were presented on a computer-controlled Barco colour monitor (Type HIREM), one stimulus to each side of a fixation point. The colours were presented in square patches, subtending 2 deg at the eye; the inner edge of each square was 1 deg from the fixation point. The luminance of all the stimuli was $15\,\mathrm{cd\,m^{-2}}$. In Experiment 1 a dim white background field of $1\,\mathrm{cd\,m^{-2}}$ was present. In Experiment 2 the background was dark.

A set of 16 colours was used in Experiment 1 and a set of 13 in Experiment 2. On half the trials the two stimulus patches were identical in colour; each particular colour could occur with equal frequency. On the remaining half of the trials the stimulus patches were of different colour; each possible pairing occurred once within a given block of trials. 'Same' and 'Different' trials were randomly intermixed. The subject was required to press one of two keys according to whether or not the colours were the same. Feedback about the correctness of responses was given, in that an error attracted an unpleasant beep. Error rates were of the order of 2%. Only 'Different' responses were used in the present analysis; the 'Same' trials serve to oblige the subject to make a true discrimination. The values entered into the multidimensional scaling (MDS) program were the medians of all reaction times for a given pair of colours. These values were typically in the range 350 to 1000 ms. Erroneous responses were excluded from the analysis of the reaction times.

Over the course of months, the colour display showed small variations in the functions relating the luminance outputs of the three guns to the signals submitted by the computer; therefore we made fresh calibrations before each series of measurements for a given observer, and adjusted the colour tables to maintain constant chromaticities at output.

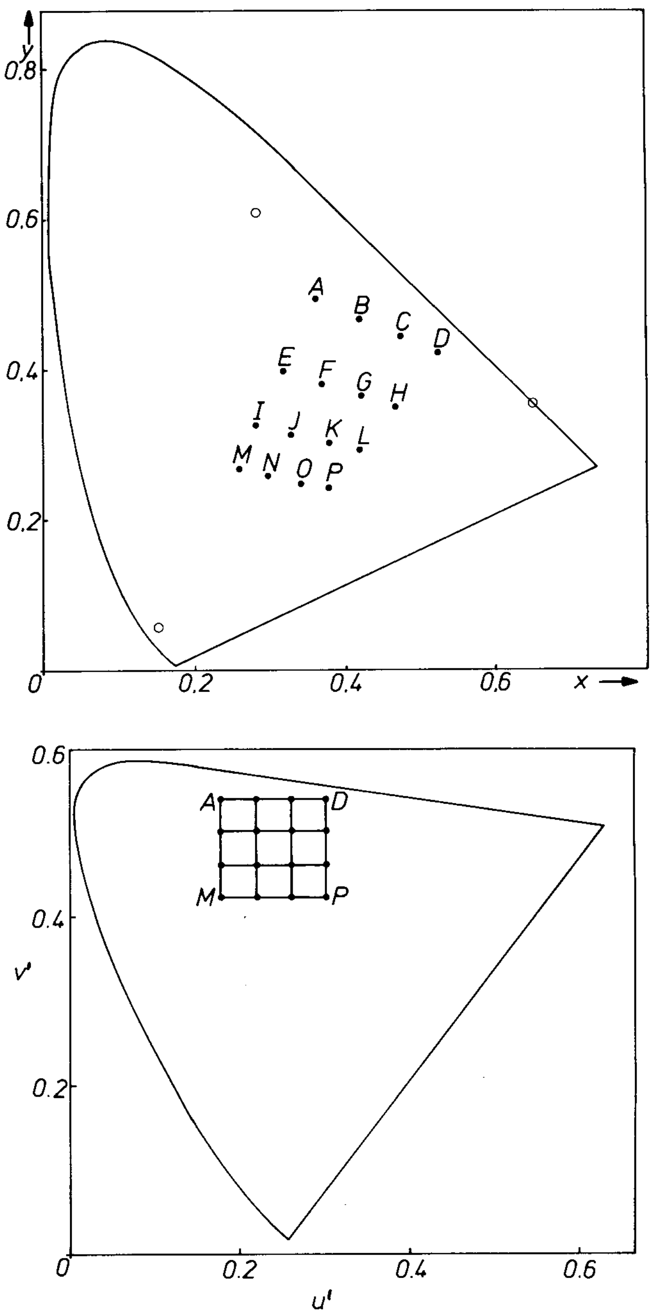

Fig. 1. (a) The set of chromaticities (A . . . P) used in Experiment 1, plotted in the CIE *x, y* chromaticity space. The three open circles indicate the chromaticities of the phosphors of the colour monitor. (b) The set of chromaticities (A . . . P) used in Experiment 1, replotted in the CIE *u′, v′* 'uniform colour space'. The stimuli were explicitly chosen to form a regular matrix in this space.

Table 1. The chromaticity coordinates of the stimuli used in Experiment 1

	x	y		x	y
A	0·362	0·491	I	0·280	0·324
B	0·420	0·466	J	0·330	0·311
C	0·473	0·443	K	0·375	0·299
D	0.521	0·422	L	0·417	0·288
E	0·316	0·397	M	0·259	0·266
F	0·369	0·379	N	0·297	0·256
G	0·419	0·363	O	0·340	0·247
H	0·464	0·348	P	0·379	0·239

The two subjects, the authors, both score normally on the Farnsworth–Munsell 100-hue test of colour vision.

3 Results

3.1 Experiment 1

The set of 16 colours used in this experiment are shown in the chromaticity diagram of Fig. 1(a); the x and y coordinates are listed in Table 1. We deliberately chose the stimuli to lie in a regular matrix in the CIE u',v' uniform chromaticity space (Fig. 1(b)). In addition, subsets of the stimuli were chosen to lie along lines that are theoretically interesting. The stimuli EFGH lie along a protan confusion line; that is to say, they would appear to be of identical hue to a colour-blind observer who lacked the long-wave cones. The stimuli CGKO lie along a tritan confusion line; that is to say, they would be confused by a colour-blind observer who lacked the short-wave cones. When a normal observer makes discriminations along the line CGKO he must be using his short-wave cones.

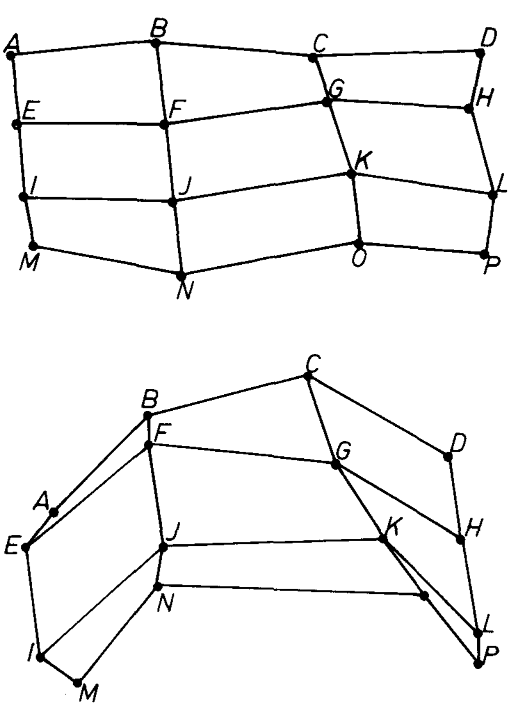

Fig. 2. Results of Experiment 1 for observers C.R.C. (upper panel) and J.D.M. (lower panel). The plots show the two-dimensional solutions given by the multidimensional scaling program KYST. For a given observer, the distance between any two chromaticities in the derived space is inversely related to the reaction time taken to discriminate them. Distance is expressed in arbitrary units, these being the same for the two dimensions of the space.

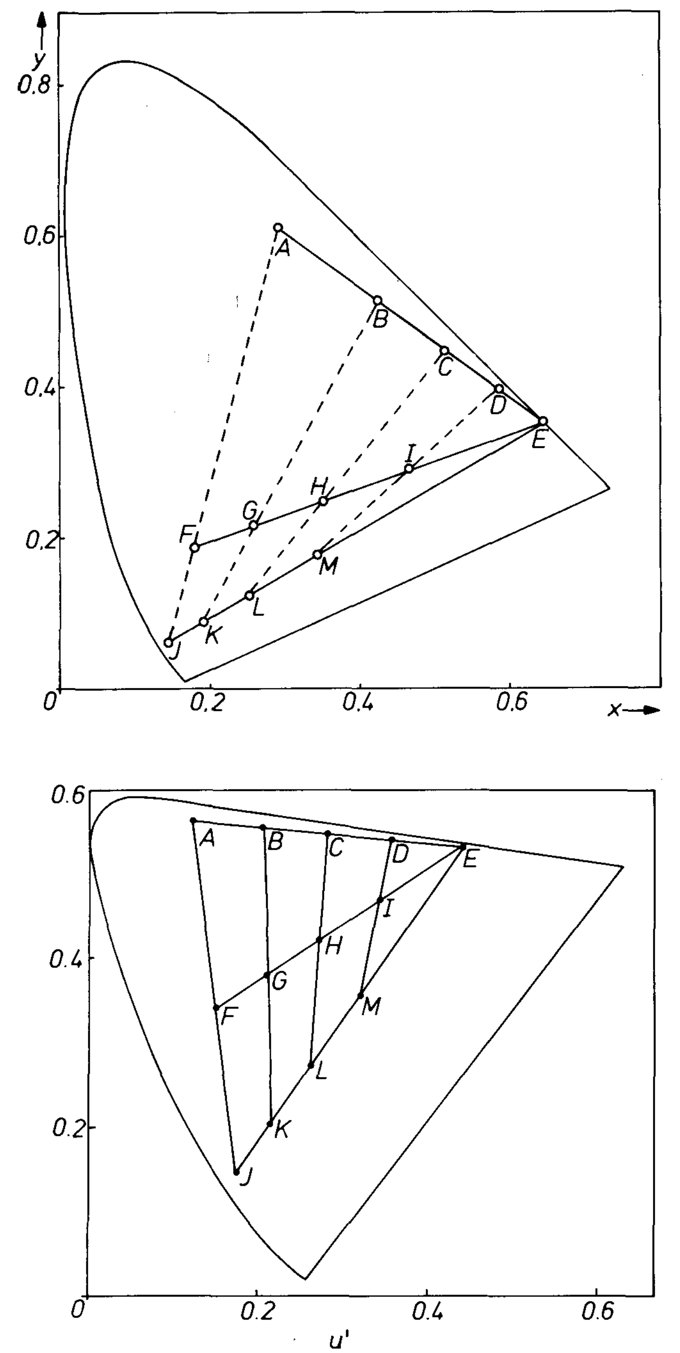

Fig. 3. (a) The set of chromaticities (A . . . M) used in Experiment 2, plotted in the CIE x, y chromaticity space.
(b) The set of chromaticities (A . . . M) used in Experiment 2, replotted in the CIE u', v' 'uniform colour space'.

In the case of subject C.R.C. each possible pair of colours was presented a total of 60 times over the course of successive blocks of trials; in the case of J.D.M., each pair was presented 80 times.

Figure 2 shows, separately for each subject, the result of a two-dimensional MDS analysis of the reaction times. In both cases the MDS program is impressively able to recover the topological structure of the original matrix without even local inversions of the ordering. This result demonstrates that discriminative reaction times are lawfully related to the ordering of the colours in the chromaticity space. There is, however, some difference between the two subjects, the reaction-time space for J.D.M. being systematically curved.

Table 2. The chromaticity coordinates of the stimuli used in Experiment 2

	x	y		x	y
A	0·290	0·603	H	0·352	0·243
B	0·424	0·510	I	0·465	0·286
C	0·513	0·446	J	0·148	0·054
D	0·584	0·395	K	0·192	0·081
E	0·647	0·351	L	0·254	0·118
F	0·181	0·182	M	0·345	0·172
G	0·260	0·210			

It is apparent from Fig. 2 that the spacing of stimuli in the CIE u',v' diagram does not accurately predict the reaction times for discriminating supra-threshold colour differences. For both subjects the space derived from the reaction times is contracted in a direction that corresponds approximately with the directions of tritan confusion lines in the chromaticity diagram. The practical implication of this result is clear: if the designer cannot avoid using stimuli that lie along a tritan confusion line (i.e. stimuli that can be discriminated only by the short-wave cones), then he must separate them widely in the chromaticity diagram; otherwise the operator's responses will be significantly slowed.

3.2 Experiment 2

Guided by the results of Experiment 1 we have tried to choose a set of colours that would be more uniformly separated in a space based on reaction times. The 13 chromaticities chosen for this second experiment are shown in Fig. 3(a); and in Fig. 3(b) they are replotted in the CIE u',v' uniform colour space. The x and y coordinates are listed in Table 2. For C.R.C. the results are based on 50 repetitions of each possible pair of colours, and for J.D.M. they are based on 90 repetitions.

Figure 4 shows the solutions given by a two-dimensional MDS analysis of the median reaction times. Results for subject C.R.C. are shown in the upper panel, those for J.D.M. in the lower panel. Again the MDS program recovers the topology—the ordering—of the colours without error. The solutions are similar for the two subjects, and, if stimulus E is excluded, we have a set of twelve colours that are relatively uniformly spaced in terms of their discriminabilities.

4 Conclusions

Our present results suggest that it will be feasible to derive the space that we propose, a space in which colours that are equally separated are colours that require the same time to be discriminated. But already our results give guidance as to how a set of, say, 12 or 16 stimuli should be placed in chromaticity space if speed of discrimination is to be maximized.

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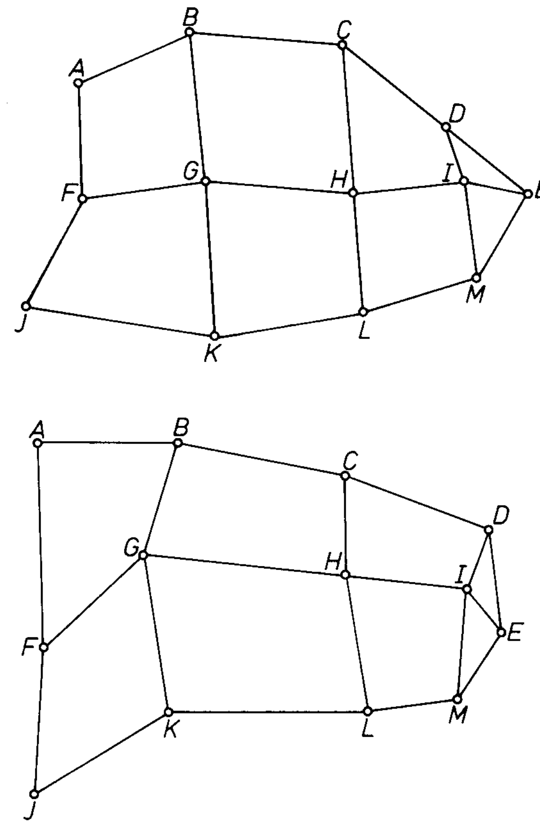

Fig. 4. Results of Experiment 2 for observers C.R.C. (upper panel) and J.D.M. (lower panel). For explanation see legend to Fig. 2.

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