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The gap effect: chromatic and achromatic visual discrimination as affected by field separation

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Abstract. The effect upon visual discrimination of slightly separating the fields to be compared was tested for three conditions. Luminance discrimination was impaired, but chromatic discriminations were either unaffected or improved, depending upon the colours used. The results are explained in terms of three factors (distance, contour enhancement, averaging), two of which can be expected to behave differentially, depending upon the nature of the discrimination.

1. Introduction

The finest luminance discriminations are known to require a careful alignment and juxtaposition of the fields to be compared. For example, Walsh [1] writes:

> " For accuracy of measurement it is necessary that the line of division [between the two fields being compared] should be as fine as possible; hence the surfaces should neither overlap in such a way as to produce a bright band between them, nor, on the other hand, should they be separated by a dark band or line of appreciable breadth " (p. 195). Referring to his own data, LeGrand [2] states:
>
> " With a large field of view, a sufficiently high value of luminance and good adaptation to this luminance, the difference threshold $\Delta L/L$, measured by the method of mean error, may be as low as about 0·005. This is only possible if there is no dark line of separation between the parts of the field... the threshold is doubled if there is a line of separation with a width of three minutes, while it is quadrupled if this width is 30′ " (p. 276).

When discriminations are based upon chromaticity rather than luminance differences, there is uncertainty about what happens. Judd [3] states that the presence of a conspicuous line interferes significantly with colour discrimination, although less so than for luminance differences. In a recent study Sharpe and Wyszecki [4] agree with this conclusion. Traub and Balinkin [5], on the other hand, found no effect of field separation over a range from zero to nearly one degree of visual angle, although only three pairs were tested where chromaticity alone was varied.

All of these studies suffered from the limitation that, even for the conditions where the stimulus fields were closest together, some kind of a dividing line remained between them. An exception, where no division was perceived between juxtaposed stimuli, was reported by Malkin and Dinsdale [6]. They used green ceramic tiles of slightly different colour joined together in pairs with an uninterrupted surface glaze. They report as follows:

> " In one set, A, the gap between the two halves was kept to a minimum by placing the ground edges in close contact. In the other set, B, a small gap was introduced between the two halves. Except for the gap size the two sets were identical, being cut from the same uniform tiles. When the sets were viewed at 45° from a distance of about 1 metre, the gap in set B was clearly visible and the colour difference in this set was easily seen. However, the gap in set A was not visible under these conditions, and the majority of observers either saw no colour difference, or a very much reduced colour difference, in this set " (p. 250).

The phenomenon of altered discriminability due to a separation between fields will be termed the *gap effect*. It will be defined as a positive effect when discriminability is improved, and as a negative effect when discriminability is impaired.

When chromaticity differences are examined, the gap effect may depend upon which colours are compared as well as upon spatial parameters. Malkin and Dinsdale, for example, do not report the positive gap effect for other than green tiles. On the other hand, Hilz and Cavonius [7] and Hilz *et al.* [8] have reported that the ability to detect differences in wavelength between the alternate stripes of a rectangular bar pattern is considerably enhanced if the wavelength difference between alternate stripes is reinforced by a small difference in luminance, continuously present and clearly perceptible. Wavelength discrimination measured this way is improved by as much as a factor of 5 by introducing 0·1 log unit of contrast (26 per cent) between the alternate bars. Over the range tested, the ratio of improvement was largely independent of wavelength, but depended considerably upon bar width. Although this is not a gap effect, it is a relevant result if one important influence of a gap is to more clearly demarcate the junction between two fields to be compared. The 26 per cent contrast difference between alternate stripes provides positive information about which area is to be associated with which particular colour.

We offer the following hypotheses as points of departure for further investigations of the gap effect. Hue has a tendency to fill in uniformly between contours, whether the contours are based upon luminance differences, chromatic differences, or an artificial dividing line. It is proposed that there exists some kind of an averaging mechanism that assigns only one mean value for the hue of a region, rather than many point-for-point values. Some further observations of Malkin and Dinsdale support this idea. They report on the appearance of other tiles whose colour was continuously and very shallowly graded. Such tiles appeared as a rectangle of a single colour until a divider was placed across them: this immediately caused a colour difference to be perceived.

A possible function of such an averaging mechanism would be to reduce the numbers of neural pathways required to transmit chromatic information in the visual system. Because the perception of a naturally occurring border is unlikely to be based upon a chromatic difference without a luminance difference also being present, there is presumably little advantage to be gained in duplicating information about sharp edges in separate chromatic channels. This idea enjoys some support from other studies. Baldwin and Nielsen [9] had observers look at pictures provided by superposition of images from red, green, and blue projectors; they found that the blue image could be substantially defocused without degrading perceived picture sharpness. Experiments of

Granger and Heurtley [10] are consistent with the hypothesis that achromatic channels, receiving input from red-sensitive (R) and green-sensitive (G) cones, carry the image detail with more precise spatial and temporal characteristics than do the chromatic channels, including those that receive input from exactly the same receptors.

Chromatic discriminations made only by the blue-sensitive (B) cones are a particularly intriguing special case. Tansley and Boynton [11] have shown that so-called ' melting ' pairs (like those observed by Boynton and Greenspon [12]) result whenever the two members of a carefully juxtaposed pair have chromaticities that plot along a tritanopic confusion locus—that is, whenever they elicit equal activation of the red-sensitive (R) and green-sensitive (G) cones. They called these ' tritan pairs '. This result implies that the blue-sensitive (B) cones are not contributors to contour perception, although they may profoundly influence the perceived hue. Contours are formed only by stimuli that activate R and G cones differentially when juxtaposed (at equal luminance as defined by the ' minimally distinct border ' (MDB) criterion [13]), probably doing so in proportion to the degree of imbalance of these two kinds of cone activity. It should be emphasized that in these studies, like those to be reported here, no residual border remained when two fields of the same luminance and chromaticity were juxtaposed. Especially in the case of melting (tritan) pairs, then, the introduction of an artificial contour between them might serve to divide the field into two distinct regions for averaging purposes; what is seen then depends upon the average colour signal from one-half of the field as distinct from that of the other half.

Luminance averaging between well-defined borders also seems to take place, as can easily be shown by dividing a shallow luminance gradient in an experiment analogous to the second one by Malkin and Dinsdale described above. Nevertheless, borders sustained by luminance steps may otherwise be very different from chromatic ones, because of border contrast effects that are mediated by lateral inhibitory mechanisms that do not operate in the same way for pure chromaticity differences. A subjective consequence of such mechanisms is that the contour between two fields of slightly different luminance is sometimes perceived in the absence of any apparent difference in brightness†.

† As contours become more visible with increasing contrast, some associated process causes the brightness difference of the two half fields to be enhanced. In LeGrand's example, no brightness difference would be perceived for a 30′ gap, assuming that the contrast were set at threshold for fields separated by only 3′. But if the fields were then brought together, a definite brightness difference would be perceived in conjunction with the border, now twice above its threshold. The surprising extent of such effects is perhaps best revealed in the Craik–Cornsweet illusion [14] where in the absence of any luminance differences over most of the display, contours are capable of producing clear brightness differences that are spatially very extensive. von Békésy [26] has suggested that the inhibitory mechanisms underlying contour enhancement are probably not the same ones that cause brightness enhancement by contour. The former, which he calls the ' Mach type ', work over very restricted regions whose dimensions seem related to those of underlying receptive fields. Brightness enhancement by contour (based on a ' Hering ' type of inhibition) extends instead over very large distances. The unexpected difficulty that we had in measuring a robust positive gap effect for tritan pairs (see Results) may have a related basis. A slight separation of such a pair dramatically increases the perceived colour difference, between the two field halves, providing that the initial difference is already above threshold. Nevertheless, the gap improves threshold discrimination only slightly, and then only when a relatively high criterion is used.

Separation of such fields would then tend to disrupt the function of the inhibitory mechansims, leading to a negative gap effect.

The existence of lateral inhibitory mechanisms is also revealed by the well-known low frequency attenuation that is found when contrast sensitivity is measured as a function of spatial frequency [14]. The lack of such attenuation when chromaticity rather than luminance is spatially modulated [15] provides evidence suggesting a lack of such lateral inhibitory mechanisms in the chromatic visual channels.

The experiments to be described constitute a direct investigation of the effects on colour discrimination caused by separating the fields to be compared. Thresholds for a colour difference between the two halves of a bipartite field were compared in two cases: (*a*) where the fields were precisely juxtaposed, and (*b*) where they were separated by a gap. The corresponding experiment for just-noticeable luminance differences was also carried out.

There were two conditions in the chromatic discrimination experiment. In one case, the two colours fell along a tritan confusion line; in the other, they fell along the long-wave spectral locus, which is a confusion line both for protanopes and deuteranopes. (We will refer to these as *tritan* and *deutan* pairs, respectively.) The tritan pairs are of special interest because at equal luminance (MDB) they produce no discriminable contour at their junction, presumably because the right and left-hand sides differ only for the blue cones whose spatial resolving power is poor [16–19]. Such a pair seemed a suitable candidate for a positive gap effect. The deutan pairs, on the other hand, stimulate the B cones to a negligible extent and thus do not suffer the spatial handicap of the tritan pair.

The hypothesis outlined above predicts that the discrimination would be improved, for the tritan chromatic pairs, by the improved definition of the field into two areas that a gap would provide. A reasonable prediction for the deutan pairs is that field separation should produce little or no effect. This is because (*a*) there is no lateral edge-sharpening process to be disturbed by the gap, and (*b*) even in the absence of a gap, clear borders are seen between such pairs. These ideas will be elaborated in the Discussion section.

2. Apparatus

The equipment developed for these experiments has certain novel features and these will be described in some detail. The general schematic layout is shown in figure 1 (*a*). At the bottom of figure 1 (*b*) a spatial 'cross section' of the fields is shown, to depict the manner in which the four channels are combined to product the desired result. Also shown in figure 1 (*b*) is the display as seen by the observer.

A set of wavelengths, λ_1, λ_2, and λ_3, were used as shown in the table. The function of the apparatus, as it relates to the appearance of the fields, will be explained for the tritan condition. The analogous arrangements were obtained for the deutan condition by substitution of interference filters: 639 for 439 nm, and 563 for 492 nm.

Light from source S (tungsten ribbon) diverges in Channel III (Ch III) and passes through interference filter λ_2 (439 nm), fixed neutral density filters ND, and a circular polarizing light analyser CA made up of a quarter-wave plate

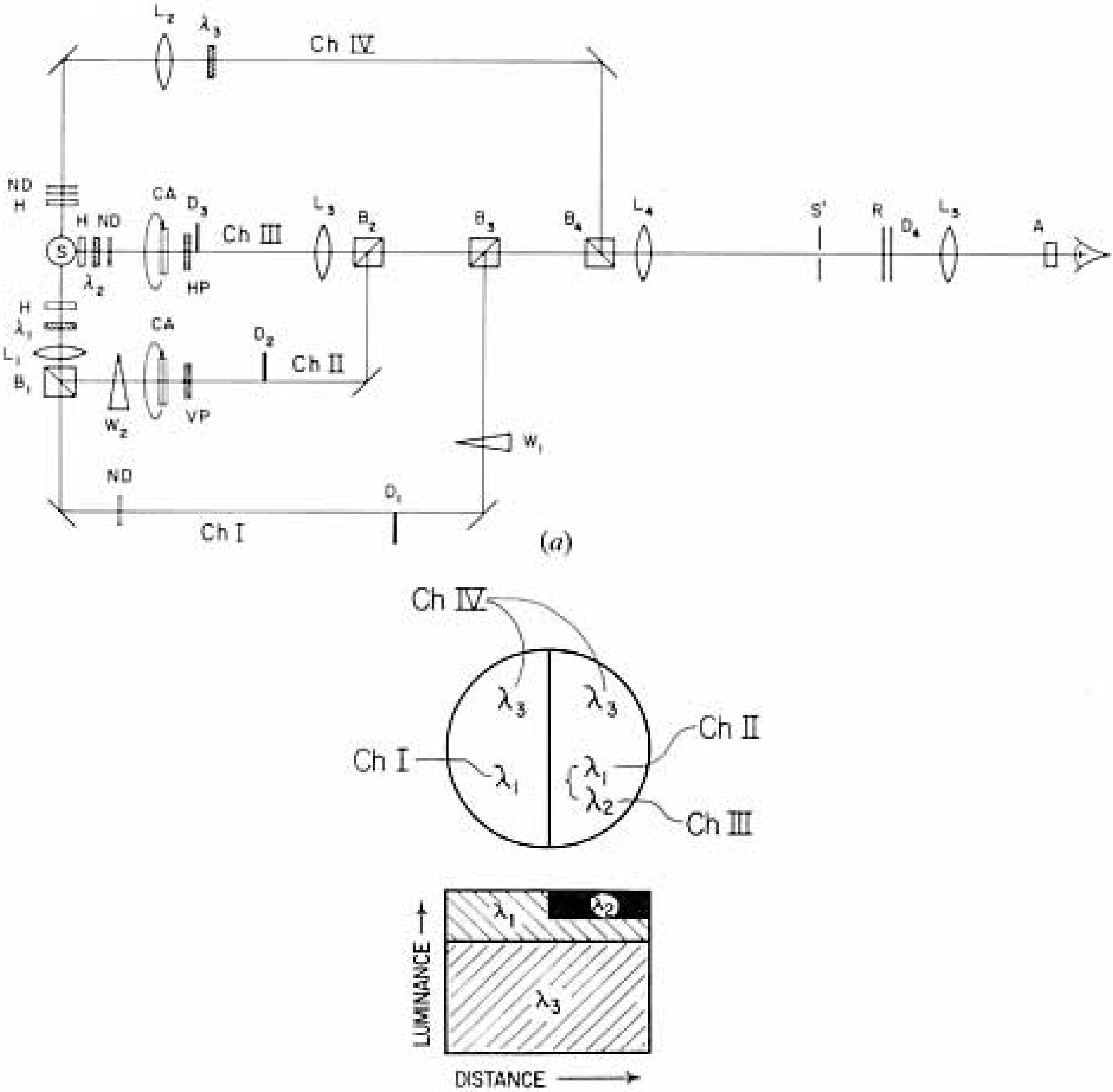

Figure 1. (*a*) Layout of the optical system used to generate the stimulus fields. A achromatizing lens, B beam splitter, CA circular analyser (rotatable), D_1 razor edge defining border of left half-field, D_2, D_3 razor edges defining border of right half-field, D_4 diaphragm defining outer edge of display, H heat absorbing glass, HP horizontal polarizer, L lens, R reticle providing vertical line (the 'gap'), S′ image of source reduced by pinhole, S tungsten source, VP vertical polarizer, W neutral wedge, λ interference filter, ND neutral density filter. (*b*) (Top) Stimulus fields as seen by the subject, showing the location of the three wavelengths of light used, and the channels through which these wavelengths were delivered. (Bottom) Cross section of stimulus fields, showing how the total luminance of the two half fields is built up from component luminances of three different wavelengths supplied by four optical channels.

The three main conditions of the experiment, showing the wavelengths and optical channels used to produce the stimulus fields.

Condition	λ_3	λ_2	λ_1
Luminance	589 nm	589 nm	Blocked
Deutan	589 nm	639 nm	563 nm
Tritan	589 nm	439 nm	492 nm
Channel	IV	III	I and II

attached, at the appropriate angle, to a linear polarizer. As the analyser rotates, light emerging from the circular analyser varies only in its angle of polarization and not in intensity. (Had a rotating linear polarizer been used alone, the intensity of light transmitted at a given angle of rotation would have depended upon the amount of incident light having that particular angle of polarization.) A sheet of polarizing material (HP) that passes only horizontally plane-polarized light is positioned following the circular analyser. As the analyser CA is rotated, the amount of light passing through HP varies with angle θ as $(1-\cos 2\theta)/2$, where $\theta = 90°$ is the position of the analyser that allows maximum transmittance. (This relation is expected theoretically and was verified experimentally.)

Other light from the source (directed ' downward ' in the diagram) passes through interference filter λ_1 (492 nm) and then is roughly collimated by lens L_1 before being reflected to the right, to form Channel II, by beam-splitter B_1. It then passes through a neutral density wedge W_2, a circular analyser, and a sheet of vertically polarizing material (VP). After first being set in opposite phase, the two analysers are driven by a single belt. The belt is driven by a motor operable at low speed by the observer. As the analysers turn, the appearance of the light following B_2 (where the channels have combined) varies continuously at constant luminance from blue (439 nm) to green (492 nm), provided that W_2 is properly adjusted.

Diaphragms D_2 and D_3 form the right side of the field as seen by the observer. D_1 in Ch I forms the left side. These have sharp edges that are defined by razor blades. Lens L_4 serves a double purpose. First, it takes the light that has been collimated by L_1, L_2, and L_3, and images it on a pinhole at S′. Secondly, it is positioned to allow the formation of a sharp virtual image at D_4 of diaphragms D_1, D_2, and D_3 (the latter as seen through L_3).

Ch I is in common with Ch II until B_1 is reached; both transmit the same spectral light determined by interference filter λ_1. The intensity of the beam in Ch I is variable by neutral filters ND and wedge W_1, the latter under direct mechanical control of the observer. The observer could also manipulate the lateral positions of D_1 and D_2, since both were mounted on horizontal slides that could be remotely controlled from the observer's position. The tilt of both D_1 and D_2 was continuously adjustable as well. These features are necessary in order to set and maintain the perfect alignment of the three edges. (Note that the diaphragms follow the circular analysers in the system; this prevents movement of the display as the analysers rotate.)

Ch I recombines at B_3 with Ch II which has been added to Ch III by beam-splitter B_2. Ch IV, containing yellow light, overlays entirely the other fields and is added to them via B_4. Source images formed independently by all four channels superimpose at S′. For the purpose of forming an image at the pupil of the eye, S′ can be considered as a new source. Lens L_5 is positioned so that the image of the pinhole in the pupil of the eye is magnified; it is circular with a diameter of 1·2 mm.

The virtual images of the edges bisect the circular field provided by D_4 which subtends 1·22° as seen by the observer. It is convenient to have two focal planes in the apparatus, one in a given channel (where D_1, D_2, or D_3 are located) and one in the common path at D_4. This arrangement allows the images from Ch II and Ch III, which make up the right-hand side of the field, to be separately adjusted so as to superimpose them exactly, with both in sharp focus.

Reticle R contains a series of vertical lines of variable width used to produce a gap. These are spaced so that when moved laterally in a horizontal slide, only one line at a time is visible. Various line widths were used, ranging from 1·8 min to 11·1 min of arc. Finally, all of the physical edges, lines, and virtual images at or near D_4 are seen by the observer, in Maxwellian view, through achromatizing lens A.

Previous efforts to provide field juxtaposition of the high quality required for MDB work, using Maxwellian view, have been unsuccessful. This system succeeds, we think, because of the common focal point at S′ which allows a single image of that pinhole (rather than four separate images) to be located at the subject's pupil. Although not theoretically impossible, it is extremely difficult in practice to superimpose four images exactly, and also to be certain that the directionality of the light is such that all four optical axes are precisely aligned. The use of the single pinhole at S′ means that the effects of small variations of this sort, which would be serious if the eye were to be placed there, are minimized.

3. Choice of stimulus wavelengths

All three stimulus variations began with light of nearly the same chromaticity and luminance. Ch IV, which provided 150 td of yellow light (except where otherwise indicated) was the dominant stimulus component. In the experiments using the method of adjustment, the deutan components added 40 td to this, and the tritan components, 15 td. (These values were substantially reduced in forced choice experiments.) The selection of 639 and 563 nm for the components of the R–G pair was arbitrary and not critical. The selection of the first member of the tritan pair was also arbitrary, since there are many pairs of short-wave monochromatic lights that fall along some tritan confusion line. But once the short-wave member of such a pair is chosen, the selection of the long-wave member becomes determined as the intersection of a line drawn in chromaticity space from the tritan copunctal point through the point representing the chromaticity of the first pair until it again intersects the curved spectral locus. Since there still exists some doubt about exactly where the tritanopic copunctal point is located [20] we tested the 439 and 492 pairs by the method of artificial tritanopia [21] using the same procedures recently described by Tansley and Boynton [11]. Following a strong bleach by a violet light (436 nm) the 439 and 492 nm fields were found to match exactly when adjusted for relative radiance. (To ensure that the bleach had not produced a condition of artificial monochromacy, a small amount of red light was added to a section of both fields and this was easily discernible.)

Given that a stimulus pair plot along a tritan confusion line, the two colours are equal in their stimulation of the R and G cones. Since these equalities are not disturbed by the added yellow (589 nm) that is supplied by Ch IV to both halves of the field, then the mixture fields of 439 + 589 nm and 492 + 589 nm will also fall along a tritan confusion line. The use of the bright yellow overlay would have the effect of minimizing any small residual artifacts that might be due to optical misalignment, though none were noted without it.

For the luminance discrimination experiments, ChI and II were blocked and the single yellow interference filter passing 589 nm was placed in the common path of Ch III and IV, after L_4. Rotation of the polarizer in Ch III then added a variable semicircle of light to that supplied by Ch IV.

4. Typical preliminary procedures

(1) With the analysers adjusted by the experimenter so that only light of 439 nm at 15 td is seen in the right-hand field, the observer adjusts the left-hand side (492 nm), to produce a MDB. He also adjusts D_1 to provide perfect spatial contiguity. The yellow overlay from Ch IV is not used during these procedures.

(2) The experimenter rotates the analysers by 90° so that the 492 nm light is now seen in both field halves. The observer adjusts W_2 to equate them for brightness and D_2 to position the borders properly. A uniform field of 492 nm light is then seen.

(3) The analysers are slowly rotated to verify that MDB is seen throughout the full range as the right-hand field changes from green to blue and also to confirm that there is no lateral shifting of the hemifields.

(4) The yellow light at 150 td is added to the entire field. The right side matches the left if the polarizers are set to the reference position.

(5) By turning the analysers, the observer causes the chromaticity of the right-hand field to change, always at MDB, and also at constant luminance†. When the method of adjustment is used, the subject sets the analyser to the point where a just-noticeable difference is judged to be present; otherwise the experimenter sets the analysers to any desired position.

For the tritan pair, discrimination thresholds were measured in terms of the retinal illuminance of the 439 nm component of the 439+492 nm mixture seen on the right-hand side of the field. The corresponding wavelengths for the deutan pair were 639 nm and 639+563 nm. The chromatic discrimination thresholds thus are not increment thresholds in the usual sense; instead, they are the threshold amounts of the 439 nm or 639 nm components that partially replaced the original 492 or 563 nm components in fields of constant luminance‡. The gap effect is the ratio of these threshold quantities for separated/juxtaposed conditions.

† Wagner and Boynton [13] showed a close correspondence between spectral sensitivity as measured by flicker photometry and minimally distinct border; both of these agreed well with Judd's modification [27] of the CIE photopic luminous efficiency function, V_λ, according to which luminance is defined. The MDB operation therefore defines equal luminance, to the extent that the spectral sensitivity of an individual subject agrees with V_λ. For the lack of a better term, *luminance* is used in this paper to describe values obtained according to the MDB criterion. Luminance was measured directly for the 589 stimulus; other values were set by MDB in relation to it.

‡ In many other studies of chromatic discrimination in the absence of luminance changes, starting with MacAdam in 1942 and continuing to Sharpe and Wyzsecki [4], it has become conventional to represent such thresholds in terms of chromaticity differences. Although it would be possible to represent our chromatic measurements in chromaticity space, we do not consider it particularly useful for present purposes to do so. Nor are the absolute values of the threshold luminances of any obvious importance in relation to the issues under examination. For those who may have an interest in more complete data, the threshold luminances have been tabulated and are available from the authors upon request.

5. Experiment 1: ratings

For each of the three major conditions (tritan, deutan and luminance) a randomized series of presentations was judged by RMB on a 5-point scale as follows:

1—fields definitely the same,

2—fields probably the same,

3—uncertain,

4—fields probably differ,

5—fields definitely differ.

Juxtaposed and separated fields were used in alternate series.

Figure 2 shows the results of the rating experiment. As expected, for the tritan pair the effect of slightly separating the fields with a 2·7′ gap is to enhance the perceived difference between the two parts of the field. For the deutan

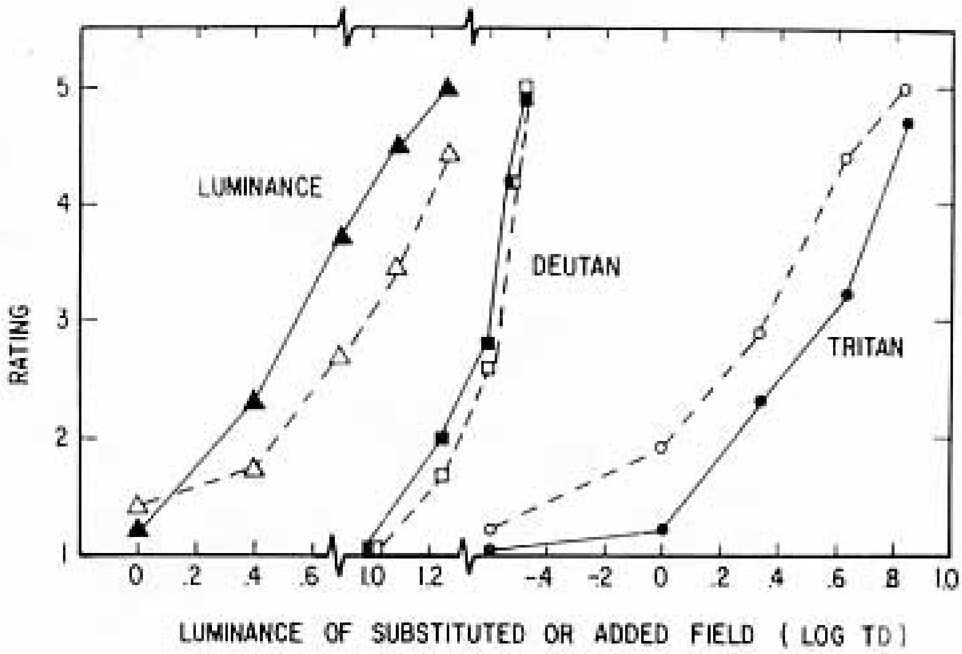

Figure 2. Results of a rating experiment for subject R.M.B. A rating of 1 was used to describe fields that appeared definitely the same; 5 was used for fields that definitely differed. The open symbols show the mean ratings for the condition where the stimulus fields were separated by a gap of 2·7′; filled symbols are for carefully juxtaposed fields. The graphs show that the gap effect is negative for the luminance condition, nearly absent for the deutan condition, and positive for the tritan condition.

pair there is no clear difference. For the luminance pair, the narrow gap reduces the perceived difference. Using a rating of '3' as a criterion, the results may be summarized as follows:

Condition	Gap width	Log gap effect
Luminance	2·7′	−0·24
Deutan	2·7′	−0·04
	11·1′	−0·10
Tritan	2·7′	+0·22

The values in the third column correspond to the lateral separations of the curves of figure 2 and one other condition (deutan, 11·1′ gap) that was not plotted. These are in log units; a positive value means that separating the fields improves discrimination, in the sense that the log luminance of the 439 or 639 nm component must be reduced by the amount shown in order to keep the judged difference at the same criterion level as for the juxtaposed fields. The results indicate that field separation decreases discriminability for the luminance and deutan condition, but improves it for the tritan condition.

The judgments are qualitatively different for juxtaposed versus separated fields, and the rating technique cannot be said to be free of all possible bias, despite the highly regular appearance of the data. Although the result confirms what had already been informally observed, and gives some idea of the order of magnitude of the observed effects, the technique was not judged to be sufficiently objective to be used on additional experienced subjects, and it was thought to be too difficult to use with naïve observers.

6. Experiment 2: method of adjustment

In these experiments the subject was given control of the circular analysers and was asked to make repeated settings. For the chromatic discriminations these settings determined the amount of substituted light of 439 or 639 nm required to produce a just-noticeable difference. For the luminance discriminations, a setting varied the amount of light of 589 nm that was added to the variable field. Seven subjects participated in various parts of these experiments.

6.1. *Experiment 2A: 1·2° field, gap of 2·7′*

Five subjects were used for all three main conditions. Three of these were paid subjects. Of these, J.A. and K.S. were naïve and T.S., though an experienced psychophysical observer, was disinterested in the experimental outcome. Two of the authors also participated.

The results are shown in figure 3 as the logarithm of the gap effect. Data are grouped into three panels, according to main conditions, with the individual data for the five subjects shown in the same order within each panel. (An additional point for a naïve subject S.C. is shown in panel (*a*); this subject did not participate under the chromatic conditions.) For example, the third data point from the left, is for subject K.S. under the luminance discrimination condition. She showed a negative gap effect of 0·3 log unit, which means that her contrast threshold was doubled by the introduction of the gap of 2·7′ of arc. The error bars represent ± 2 standard errors of the mean for the chromatic conditions (deutan and tritan) based on between-session variability. Because insufficient sessions were run to allow valid between-sessions estimates for the luminance discrimination condition, these error bars are based on within-session variability.

The results indicate that, in agreement with previous studies, luminance discrimination is more impaired than chromatic discrimination by the introduction of a gap. But the deutan discrimination is more impaired than the tritan one, and three of the five subjects show an improvement in discrimination (a positive gap effect) for the tritan pair. Subject R.M.B.'s data for the method of adjustment are in substantial agreement with his ratings in Experiment 1.

In the deutan and tritan conditions, a curious and probably significant phenomenon could be observed if the gap was moved away from the border to a position slightly inside one of the half-fields. The two regions separated by the gap tended each to appear uniform in colour, even though one of them contained a chromatic border.

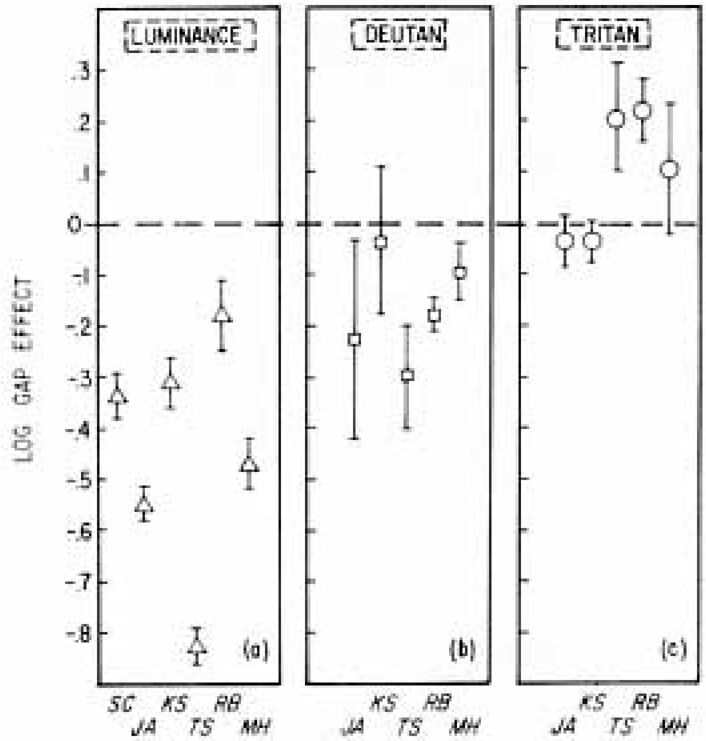

Figure 3. Gap effect obtained by method of adjustment for several subjects under the three main conditions of the experiment. The gap effect (shown here in logarithmic units) is the ratio of the threshold with a gap, divided by the Ch III threshold without a gap. The results, overall, are in reasonable agreement with the rating data of R.M.B., in that a gap improves tritan discrimination, has a slightly negative effect for deutan discrimination, and a larger negative effect for luminance discrimination. Error bars are ± 2 S.E.M. Luminance of Ch IV (589 nm) for S.C. was 100 td, instead of 150 td as for the other subjects.

In experiments on the effect of varying the gap width from 1·8′ to 8·9′, the gap effect showed no clear tendency to increase or to decrease over this range of width. Since gap width seemed not to be an important parameter, we kept the 2·7′ gap for most of our observations.

6.2. *Experiment 2B: Small fields, gap of 2·7′*

The fields to be compared were reduced to two strips each, 1·2° high and 21′ wide. For the gap conditions, these fields were separated by 2·7′, their area remaining constant. Two of the authors and one naïve subject were used in the experiment. The experimental procedures were the same as those described above, except that occasional 'catch' trials were introduced for naïve subject S.C. On these catch trials, which were about 10 per cent of the total, the circular analyser did not move when S.C. depressed the switch that normally caused such movement to occur; consequently no physical difference was introduced between the two fields. S.C. made only one false alarm response in a total of 50 catch trials.

The results are shown in the three panels at the left in figure 4. Each panel is for a single subject. For comparison, the large field effects shown in figure 3 are shown again here. All subjects give a positive gap effect for the tritan condition, and the two experienced subjects now show a positive effect also for the deutan condition. The luminance gap effect is about zero for small fields for two of the subjects, a result that should be compared to the substantial negative effects that are consistently obtained for large fields.

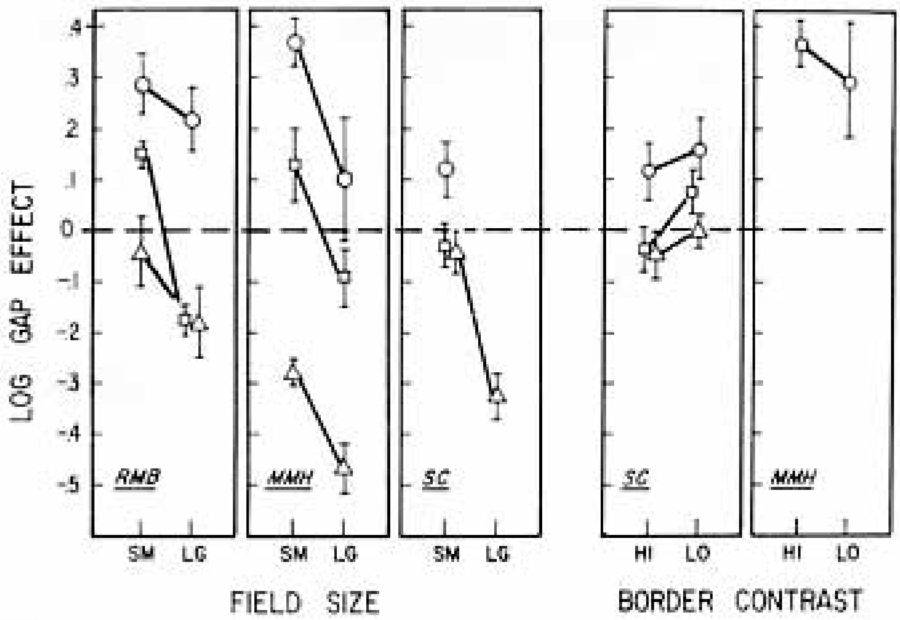

Figure 4. The effect of field size and border contrast upon discrimination for three subjects. Ordinate: gap effect in logarithmic units, as in figure 3. The method of adjustment was used. Triangles: luminance condition; squares: deutan condition; circles: tritan condition. SM = small field. LG = large field. HI = high contrast. LO = low contrast.

Some trials were run in which the negative contrast of the strip separating the fields was reduced from 100 per cent (totally dark) to about 30 per cent by causing the yellow overlay from Ch IV, which normally added light only to the stimulus fields, to enter the final optical path on the subject's side of L_4 and thus illuminate also the area separating the fields. It can be seen from the two panels at the right of figure 4 (which include the high contrast, small field data at the left) that there is no significant effect of such contrast reduction.

6.3. *Experiment 2C: Very narrow fields*

The outer flanks of the stimulus field were masked to produce a rectangular field of either 13·6′ or 16·3′ width and 1·22° height. In the juxtaposed condition the fields to be compared each filled half of this long, narrow (13·6′) field. In the gap condition the gap split the wider (16·3′) field into two 6·8′ vertical strips separated by a dark line of 2·7′ width. The illuminated areas were therefore identical in both conditions.

RMB served as subject. With the yellow overlay at 150 td, as in the experiments so far described, discriminations were impossible. With the yellow overlay reduced to 38 td, a small positive gap effect (0·14 log unit) was found for the deutan condition, and a very small and probably insignificant negative effect (0·07 log unit) was found for the luminance condition. The subjective impression in both cases was one of enormous interference with the discrimination caused by the very high contrast flanking edges. Differences that were well below threshold could be easily seen upon removal of the field mask.

The most interesting result occurred for the tritan condition. Here the discrimination continued to be impossible, even when the yellow overlay was completely removed. As the 13·6′ window was moved from left to right across the large field (which was now 492 nm on the left and 439 nm on the right) green was seen, so long as the slit overlay the 492 nm field. In the critical border region, continued movement of the slit caused the hue to change gradually from green to blue. But for any particular position of the slit the field appeared to be completely uniform in hue.

7. Experiment 3: forced choice

The results obtained by the method of adjustment could be criticized on the grounds that the subjects' criteria are not fully controlled. A conventional procedure for circumventing this difficulty is to use the method of forced choice.

Because the luminances of Ch II and III could be varied only in discrete steps it was decided to influence the probability of correct reponses by varying instead the luminance of the yellow overlay in Ch IV. Four intervals of 1 sec duration were separated by 800 ms periods. The flash intervals were demarcated by acoustic signals superposed on white noise, delivered binaurally through earphones. (Control experiments were done to ensure that discrimination was at chance levels in the absence of visual information.) Homogeneous fields were presented in the first and second intervals. In either the third or fourth interval, randomly determined, a pre-set amount of the 439 or 639 nm component was substituted in the right-hand field. (A 598 nm component was added for the luminance condition.) The observer was required to choose in which of these intervals he perceived a difference between the two halves of the field; when in doubt, he was forced to guess. Feedback was provided in the form of an auditory signal on incorrect trials. A gap width of 2·7′ was used throughout.

Preliminary observations established that discrimination was possible with extremely low luminances in Ch I, II, and III. To obtain the data to be reported, filters of density 1·8 were added to Ch II and III, reducing the luminances of the 439 and 639 components to 0·24 and 0·63 td, respectively. The luminance of Ch IV, the yellow overlay, was then varied in the range from 40 to 100 td. (For the luminance condition sufficient neutral filtering was added to Ch I to produce a just detectable increment with 100 td in Ch IV.)

These observations turned out to be subjectively very difficult, whether or not there was a gap between the fields. With juxtaposed fields there was seldom any impression of a contour between the fields for any of the three conditions examined. Sometimes the left half of the field was the one that appeared to exhibit the change of colour, although no physical change ever occurred there.

The data to be reported are based on 100 trials per data point and are from experiments with two of the authors, both highly experienced observers, as subjects. Fluctuations in sensitivity over the course of the long sessions that were required for data collection resulted in ragged frequency of seeing curves. For this reason the results are presented in a manner designed best to show the gap effect. As an example, consider the luminance condition for RMB in figure 5. The ordinate shows the percentage of correct responses in the gap condition; the abscissa shows this percentage for the juxtaposed condition. Consider the uppermost point: this represents the paired results, for presence or absence of a gap, for otherwise identical stimulus conditions (luminance discrimination for RMB). In this case there were 92 per cent correct responses with the gap, 80 per cent correct without it. In general, points falling above and to the left of the diagonal line indicate that the gap aided discrimination (a positive gap effect) whereas those below and to the right reveal a negative gap effect.

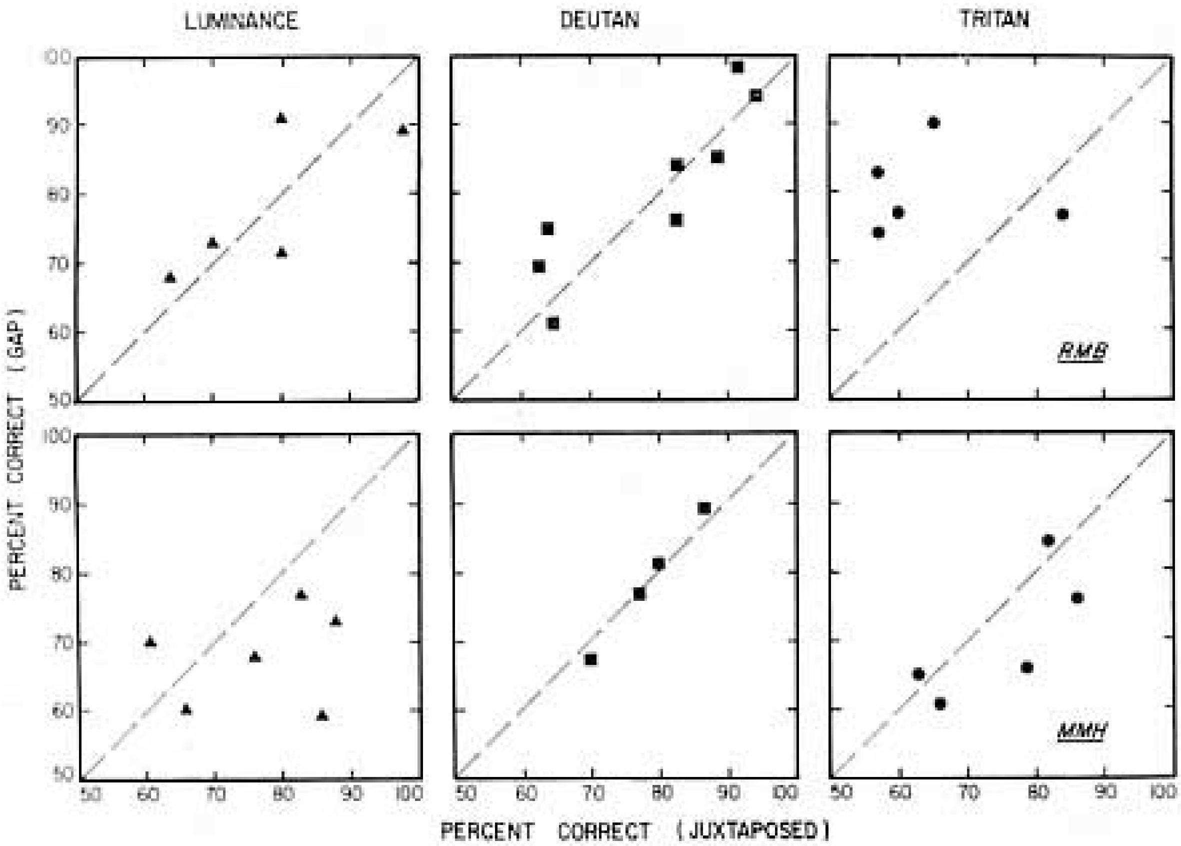

Figure 5. Results of the forced-choice experiment. Per cent correct discriminations (two alternative) with a gap of 2·7′ (ordinates) is plotted against per cent correct with juxtaposed fields (abscissae). Each panel is for one of the three main conditions of the experiment, for one of two subjects used. A positive gap effect corresponds to points above the dotted lines.

Figure 5 indicates that when forced choice is used there is essentially no gap effect for any of the three main experimental conditions. There is perhaps a suggestion of a positive gap effect for RMB for the tritan condition, where four points fall well to the upper left. But a discrepant fifth point lying well below the diagonal line, combined with the lack of any effect for MMH under the same condition, does not allow positive conclusions to be drawn. Similar statements can be made about luminance discrimination for MMH, where there is a suggestion of a negative gap effect. Overall, in figure 5 there are 16 points above, 15 points below and 1 that falls on the line.

8. Discussion

The general result of the experiments using the method of adjustment is that the gap effect is substantially negative for the luminance condition, less negative for the deutan condition, and either negligible or positive (depending upon subject) for the tritan condition. This order of luminance–deutan–tritan is invariable. The smaller the fields, the less negative (or more positive) is the gap effect. Forced choice produces much lower thresholds and eradicates gap effects under all three conditions of the experiment.

We can identify three factors that might lead to a gap effect: (1) a distance factor, (2) contour enhancement, and (3) averaging.

(1) *Distance factor.* Separation of the fields to be compared may directly reduce sensitivity to colour differences: the greater the separation, the more difficult the comparison. A huge gap, for example, would require eye movements

as a bridge, as well as colour memory. Moreover, comparisons between separated fields are physiologically very different from comparisons between adjacent fields. Since only transient stimuli evoke responses at central stages of the visual pathway, vision depends on the transient stimulation which eye motion creates at the boundaries between surfaces [14, 22]. With juxtaposed fields the presence of such transients at the boundary can serve as a cue to non-identity of the fields, making the judgement essentially a detection rather than a true comparison. (The advantage gained by transient detection with juxtaposed fields must be small, however: it is removed by stabilizing the retinal image, yet the gap effect (for the bar widths considered here) is apparently little changed by this manoeuvre [23, 24].)

We assume that a given field separation would impair all three discriminations (deutan, tritan, and luminance) to the same extent.

(2) *Contour enhancement.* Lateral inhibitory processes in the retina, of the sort that are believed to underlie the appearance of Mach bands and enhance contours, are probably operative only for the luminance condition. In addition to the evidence cited in the Introduction, this notion is supported by our subjective observation of fields at MDB under conditions where colour differences are large. Each half of such fields tends to look uniform, whereas an achromatic difference that produces an equivalent border distinctness causes a characteristic darkening of the field of lower luminance that is seen only in the neighbourhood of the border. Introducing a gap would have no effect on contour enhancement for the chromatic pairs, since there is none to begin with. But a gap may be assumed to eliminate, or at least markedly interfere with, the lateral inhibitory processes that are effective for the juxtaposed fields. The contour sharpening factor will consequently make the gap effect for the luminance discrimination more strongly negative.

(3) *Averaging.* Suppose some mechanism assesses an average value for each of the two fields, and presents this information to the discriminator. Some reasons for postulating a process of this sort were given in the Introduction. Such a mechanism will harm discrimination to the extent that it combines, in the average, colour information that properly belongs on the other side of a border. For the luminance condition (and perhaps to a lesser extent for the deutan pair) a distinct border is always seen, one that should restrict the averaging process separately to each half-field. For the tritan condition, however, no distinct border is normally apparent that can guide the averaging mechanism. Introducing a gap should therefore serve to improve discrimination for the tritan condition by restricting the averaging process to the appropriate field halves. Since the gap now serves to eliminate false averaging, substituting instead useful selective averages, we expect a positive gap effect for the tritan condition. For the luminance and deutan conditions, appropriate averaging already occurs and makes no contribution to a gap effect, either positive or negative.

The transition from a negative gap effect in the luminance condition to a positive one in the tritan condition is thus explained without invoking any difference between the three conditions except for the already well-documented failure of purely chromatic differences to form sharp borders enhanced by lateral inhibition. In accordance with this view, a positive gap effect may be observed in luminance discrimination situations if the achromatic gradient between the fields is too gradual to form a distinct border: an example of this is the Koffka–Benussi ring for demonstrating simultaneous contrast [25].

To summarize: (1) for luminance discrimination the distance factor and contour sharpening will give a negative gap effect. (2) For the deutan condition the distance factor only contributes to a gap effect, which will consequently be smaller than (1). (3) For the tritan condition the distance factor and the averaging mechanism work in opposition, giving a gap effect close to zero or even positive.

8.1. *Small fields*

Our work with small fields was not sufficiently extensive nor complete (see figure 4) for us to say whether there is an interaction between this variable and the main conditions of the experiment. So far as we can tell, the gap effect becomes relatively more positive for all three conditions when the fields are made smaller. A probable explanation is that, without a gap, inappropriate averaging becomes more serious for all three conditions, and we thought that part of the reason for this might be an interference of the contour separating the two field halves by the high contrast flanking contours which are brought very close to the location of the critical discrimination. It was for this reason that we did a few low contrast experiments for which data are shown at the right in figure 4. Although discrimination was improved, the gap effect was not significantly changed by the contrast manipulation. This result, for the luminance condition, disagrees with one of Judd [3] who found less of a negative gap effect when a low contrast division was used. See also Sharpe and Wyszecki [4].

8.2. *Forced choice results*

What happened to the gap effect under the forced-choice conditions? There appear to be four possible explanations.

(1) The gap effect as observed with the method of adjustment is an artifact, perhaps caused by subjects' bias; when this is controlled by using forced-choice, the gap effect is shown actually not to occur.

(2) Flashing the stimuli, which was done only under the forced-choice condition, for some reason destroys the gap effect.

(3) The gap effect is real, but observable only at stimulus intensities that are somewhat suprathreshold. It disappears for the extremely small luminance and chromaticity differences characteristic of the forced-choice procedure.

(4) Incorrect decisions in the forced-choice situation are presumably caused by chance fluctuations in some physiological signals that represent the pertinent aspect (luminance or colour) of the two stimuli compared. If these fluctuations are already present in the signal before the processes responsible for the gap effect operate on it (for instance if they originate from photon noise), then a gap might increase the signal (positive gap effect) or decrease it (negative gap effect) without affecting the reliability of discrimination. The increase or decrease would affect the true signal and the ' noise ' alike.

Each of these possibilities will now be discussed.

(1) If the gap effect is an artifact due to subjects' bias, the results obtained from three naïve subjects using the method of adjustment cannot be explained. Also difficult to explain are the regularity of RMB's rating data (which exhibit a near absence of false reports of differences where none physically existed), and

our observations with the very narrow field. Moreover, the experienced subjects had no strong expectations concerning whether the outcome of the deutan condition should resemble that of the tritan or luminance condition, if either. The general agreement between RMB's rating data and the adjustment data of the other subjects does not appear to be fortuitous.

(2) RMB made settings by the method of adjustment, not reported above, to check on the flashing hypotheses. The luminance condition alone was examined. The average results from two experimental sessions show a negative gap effect averaging 0·50 log unit for the steady condition, and 0·22 log unit for the flashed condition. This result suggests that flashing the stimuli reduces, but does not eliminate, the negative gap effect.

(3) Several considerations tend to support the hypothesis that the gap effect disappears under forced-choice conditions only as an indirect effect of the method, one which is related to the very small chromaticity and luminance differences to be discriminated.

(*a*) It is possible that lateral inhibitory mechanisms, whose disruption caused a negative gap effect at suprathreshold contrast levels, do not function well at the ultimate limits of detection that are reached with forced-choice procedures [26].

(*b*) The results are consistent with the subjective observation, using forced-choice procedures,that the perceived differences between the two fields are not localized at or near the gap that separates them.

(*c*) If no border is seen, as seems to be the case for juxtaposed fields under forced choice, then there is no basis for an averaging mechanism to enhance the perceived differences between the two fields. In the juxtaposed field condition, only one field is seen, and some kind of change (often indescribable) occurs in some part of it.

(*d*) The rating data for the luminance condition (but not for the tritan condition—see (4) below) show a decrease in the gap effect at the lowest contrast levels (figure 2).

(4) The idea that the gap effect originates at a more central stage than the ' noise ' limiting discrimination is also consistent with most of our observations. In particular, unlike hypothesis (3) it can explain why in the tritan condition the gap effect is absent in the forced-choice data but present in the rating data at comparable contrast levels (figure 2).

Note that to adopt this hypothesis is not to dismiss the gap effect as unreal, since the effect on experience and behaviour may be real enough except under the special conditions of a forced-choice experiment.

8.3. *Chromaticity discrimination*

For very small fields the tritan discrimination becomes impossible, whereas the deutan one does not. This result is entirely consistent with notions of small-field tritanopia that have long been in the literature, and it is not unexpected. A more novel feature of our results is that the gap effect is different for the deutan condition than for the tritan condition. In view of this one cannot expect the relation between deutan and tritan discrimination with precisely juxtaposed fields to be exactly the same as that found with fields separated by even a slight gap. Such a slight gap was present, for example, in the classic experiments of MacAdam, and it is to be expected that the general orientation of the major axes of his ellipses toward the blue corner of the chromaticity diagram would have been further accentuated by the use of perfectly juxtaposed fields.

9. Conclusions

(1) The discriminability between chromatically different fields that are equivalent for tritanopes (tritan condition) and do not form good contours at equal luminance is enhanced in some subjects by slightly separating these fields (the positive gap effect).

(2) A negative gap effect exists for luminance discrimination, since separating the fields reduces their discriminability.

(3) Fields that are chromatically different and which also form good contours at equal luminance (deutan condition) are somewhat more difficult to discriminate when separated. This negative gap effect is smaller than that found for luminance differences, and is probably absent for very small field separations.

(4) The gap effects disappear entirely, or nearly so, when discriminations are pushed to the limit by forced-choice procedures.

(5) A model that qualitatively accounts for the results considers three factors in the discrimination process: (*a*) colour difference, (*b*) contour sharpening, and (*c*) an averaging mechanism. A gap is assumed always to make a colour difference harder to see, to interfere with contour sharpening that works only for luminance differences and juxtaposed fields, and to improve tritan discrimination by adding a contour which permits signals from the two field halves to be separately averaged.

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