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THE BREAKDOWN OF A COLOUR MATCH WITH HIGH INTENSITIES OF ADAPTATION

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INTRODUCTION

IN a paper on adaptation [Wright, 1934], it was reported that when the eye was adapted to a stimulus of considerable brightness, say above 15,000 photons, the colour-mixture equation between two patches of light was, under certain circumstances, upset. Thus, if a yellow was matched initially by a mixture of red and green, the match was found to be no longer satisfactory after adaptation, an increase in the proportion of red usually being required to equate the colours. It was also shown in the same paper that the recovery from the depressed sensitivity level induced by adaptation suffered a marked change, again mainly in the case of the red, at about the same adaptation intensity at which the colour match broke down. For moderate degrees of adaptation, the recovery curves were linear, but with increasing intensities, a pronounced irregularity developed in the case of the red. On the other hand the green curve, although it lost its linearity, showed none of the marked abnormality displayed by the red response.

It is reasonably certain that the breakdown in the yellow colour match and the irregularity in the red curve are different manifestations of the same phenomenon. There are two ways in which a colour match might be upset, (*a*) by a change in the shape of the spectral response curves (the so-called sensation curves), or (*b*) from the interposition of a colour filter, in the form of a pigment, in the optical media of the eye or, what is equivalent, by a change in colour of a pigment that already exists. It is, for instance, easy to show that the insertion of a coloured glass in the path of the light beam from a colorimeter will, in general, upset any match previously obtained.

The present paper describes measurements made in connection with the colour match breakdown, in an attempt to determine which of these alternatives is correct.

THEORY OF THE MEASUREMENTS

The method adopted in the investigation was similar to that used previously, when determining the spectral coefficient curves and white points [Wright, 1929] of a number of observers. In making these colour measurements it was found advantageous to record the relative amounts of the three instrument primaries, red, green and blue, in terms of units based on matches of two spectral radiations, a yellow and a blue-green, rather than on a white light of given energy distribution. For details of the method reference must be had to the original paper, but the fundamental advantage depends on the fact that the colour of a monochromatic radiation is unaffected by any intermediate colour filter or pigment, whereas the colour of a source with an extended spectrum, such as a tungsten lamp, will be appreciably altered. Thus in the case of the yellow macular pigment, the spectral coefficients obtained using the monochromatic units were independent of the density of the pigment, whereas with the white units the spectral coefficients varied according to the yellowness of the pigment, even when the response curves of the receptors themselves were unchanged. Further, when white is taken as the unit colour, the white point always has the same position in the colour triangle, but with the monochromatic system, the position of the white point will be a direct indication of the colour of the interposing pigments.

The application of this argument to the present problem is as follows: if the breakdown in the colour match is due to the bleaching of an intermediate pigment such as the macular pigment, then the spectral coefficients, determined on the monochromatic basis, will be the same after adaptation as before, but the white point will have shifted in a direction indicating the colour change in the pigment. On the other hand, if adaptation produces a change in the shape of the response curves, this will be revealed by a change in the spectral coefficients themselves and, in general, by a shift of the white point as well.

APPARATUS AND TECHNIQUE

The apparatus used was the author's trichromatic colorimeter [Wright, 1929] in which a 2° bipartite field is used, one half illuminated by a monochromatic radiation to act as the test colour, while the other half consists of a mixture of three radiations, at wave-lengths 0·65, 0·53 and 0·46μ, to act as the instrument primaries. The amounts of these primaries can be varied by the observer to match the test colour both in colour and intensity. Actually, when the test colour is a monochromatic radiation, a negative amount of one of the primaries is necessary to obtain a true match. A negative value cannot be determined directly, but may be found by adding sufficient of the appropriate primary to the test colour field until the mixture of test colour and desaturating primary is such that it can be matched by a positive mixture of the three primaries. A subsidiary observation is then made to determine the amount of primary added, which, on subtraction, will give the negative value desired.

In the system used in these and other observations, the amounts of red and green required to match a yellow of wave-length 0·5825μ were made equal, and similarly, the blue and green units were adjusted to be equal in a match on 0·494μ. A colour C would then be represented by an equation of the form

$$xC = \alpha R + \beta G + \gamma B,$$

where α, β and γ give the amounts of red, green and blue required to match an amount x of C, α, β and γ being, of course, measured on the units given above. In order that the equation may refer only to the colour quality and not to the intensity of C, the coefficients are divided by $(\alpha+\beta+\gamma)$ to give a unit trichromatic equation

$$C = aR + bG + cB,$$

where $$a = \frac{\alpha}{\alpha+\beta+\gamma}, \quad b = \frac{\beta}{\alpha+\beta+\gamma}, \quad c = \frac{\gamma}{\alpha+\beta+\gamma}.$$

Thus $a+b+c=1$ and the amount of C in such an equation is taken as unity. Further details of the method, with sample calculations, are given elsewhere by the author [1929].

In addition to the normal colorimeter field, an adaptation patch had to be provided. This was arranged using the same device employed in experiments on the effect of adaptation on intensity discrimination [Wright, 1935]. In this, an adapting field of 5° angular subtense could be viewed in place of the 2° colorimeter field, but on rotating a mirror the test field could be revealed momentarily. Releasing the mirror automatically brought the adapting field into view again.

To determine the effect of adaptation on the trichromatic equations of the spectral colours, the coefficients were first determined in the normal manner, by matching 0·5825 and 0·494 μ to find the units of the primaries, and then matching the radiations being tested, with, where necessary, subsidiary matches on the desaturating primary used. The eye was then light-adapted and the whole series of observations, including those on the unit colours, repeated. In order that each observation should be made under the correct adaptation conditions, the adapting field could only be removed for very short intervals, of the order of a second, to permit the colorimeter field to be seen. In practice, the eye viewed the adapting field for 3 min. and then viewed a particular test colour momentarily. The adaptation was continued, the primaries were adjusted to improve the match, the test field viewed again, and so on, until a satisfactory match was obtained for the adapted eye. While a new test colour was being provided, the observer rested; the 3-min. period of adaptation was then repeated and the new test colour rematched. Each observation was repeated three times to obtain a mean value.

All the observations were made by the author. This is an important consideration, as we have found very wide variations in certain adaptation phenomena among different observers. The origin of these variations has still to be determined.

RESULTS

The coefficients of four monochromatic radiations, 0·5825, 0·494, 0·55 and 0·61 μ, and of a white (approximately the C.I.E. S_B source) were obtained for no light adaptation and for light adaptations of 20,000 and 48,000 photons. The adapting radiation was a white with a colour temperature of approximately 2700° K. Coefficients for a white test colour are also given after white adaptations of 72,000 and 145,000 photons and a red adaptation of 90,000 photons. These results are shown in Tables I and II. Results on a different white (the C.I.E. S_A source) are given in Table III.

The selection of these monochromatic test colours was dictated by the fact that the first two had to be measured to derive the trichromatic units, while 0·55 and 0·61 μ were respectively intermediate between 0·5825 μ and the green primary, 0·53 μ, and between 0·5825 μ and the red primary, 0·65 μ. They should therefore be most sensitive to any changes of coefficients that may occur, since 0·53, 0·5825 and 0·65 μ are fixed in their red-green relation.

The measurements on the monochromatic radiations have been repeated on several occasions, although it was not thought necessary to give more than the one set of results.

TABLE I

Test colour	Primaries	Trichromatic coefficients		
		No adaptation	20,000 photons white adaptation	48,000 photons white adaptation
0·5825 μ	R	0·508	0·505	0·501
(700 photons)	G	0·508	0·505	0·501
	B	-0·016	-0·010	-0·002
0·494 μ	R	-0·148	-0·120	-0·100
(75 photons)	G	0·574	0·560	0·550
	B	0·574	0·560	0·550
0·55 μ	R	0·150	0·143	0·123
(500 photons)	G	0·876	0·879	0·908
	B	-0·026	-0·022	-0·031
0·61 μ	R	0·823	0·794	0·769
(400 photons)	G	0·180	0·200	0·213
	B	-0·003	0·006	0·018
White	R	0·199	0·201	0·134
(200 photons)	G	0·371	0·384	0·404
	B	0·430	0·415	0·462

TABLE II

Test colour	Primaries	Trichromatic coefficients			
		No adaptation	72,000 photons white adaptation	145,000 photons white adaptation	90,000 photons red adaptation
White	R	0·212	0·177	0·147	0·138
(250 photons)	G	0·344	0·348	0·420	0·411
	B	0·444	0·475	0·433	0·451

TABLE III

Test colour	Primaries	Trichromatic coefficients			
		No adaptation	20,000 photons white adaptation	40,000 photons white adaptation	80,000 photons white adaptation
White	R	0·391	0·331	0·336	0·276
(150 photons)	G	0·413	0·485	0·466	0·495
	B	0·196	0·184	0·198	0·229

DISCUSSION

In discussing these results, the first point that emerges is that the changes in coefficients of the monochromatic radiations are not a direct measure of the extent of the colour match breakdown. It was shown in the previous adaptation paper [1934], that the increase in the amount of red relative to the amount of green required in, say, a yellow match, may be very considerable; the actual change will depend on the intensity of adaptation, but the ratio of red to green may increase by 50 or 100 p.c. or more. This can be demonstrated by comparing the actual readings recorded on the colorimeter when, for example, 0·5825μ was matched both before and after the 48,000 photons white adaptation of Table I. The red and green instrument readings were as follows:

	No adaptation	48,000 photons white adaptation
Red	836	1189
Green	552	445
Red/Green	1·51	2·67

It is seen that in this case the red/green ratio has increased by 77 p.c. But when the readings are converted to trichromatic coefficients by the author's method (1929), this change is automatically removed.

It follows that whatever changes are observed in the other monochromatic coefficients, they will necessarily be only second order indications of the alteration of the response curves of the receptors. Small changes, provided they are definite, will have a correspondingly greater significance, but if no change were found it would mean that the colour match breakdown was due entirely to an interposing pigment, and not to any fundamental alteration in the response curves.

If the phenomenon is due to a modification of the actual response curves, the change of the white coefficients may be either of first or second order magnitude depending on the nature of the response change; but if it originates in a pigment change, then the whole of the effect should be shown by the white coefficients and none by the monochromatic values.

In the light of these conclusions, the results of Table I show that there is a definite change in the response curves. The coefficients of the monochromatic radiations vary systematically with increasing adaptation; in every case except the very small alteration in the blue value of 0·55μ, the changes increase as the adaptation intensity is increased.

On the other hand, the changes in the white coefficients are considerable. It is impossible to say for certain whether this indicates a pigment change as well as a change in the shape of the response curves, but on the assumption that we are dealing with a single phenomenon and not two phenomena occurring simultaneously, then the white coefficients provide some indication of the nature of the change in the response curves. The results are not as consistent as one could wish, due largely to the difficulty of getting a sufficiently bright white test colour in the apparatus, but the changes all have very similar tendencies. They are shown diagrammatically in Fig. 1. (*a*) and (*b*) show the white points of Tables I and II plotted on an enlarged section of the colour triangle and (*c*) gives the results of Table III. (*d*) shows the whole colour triangle together with the spectral locus, and indicates the mean direction

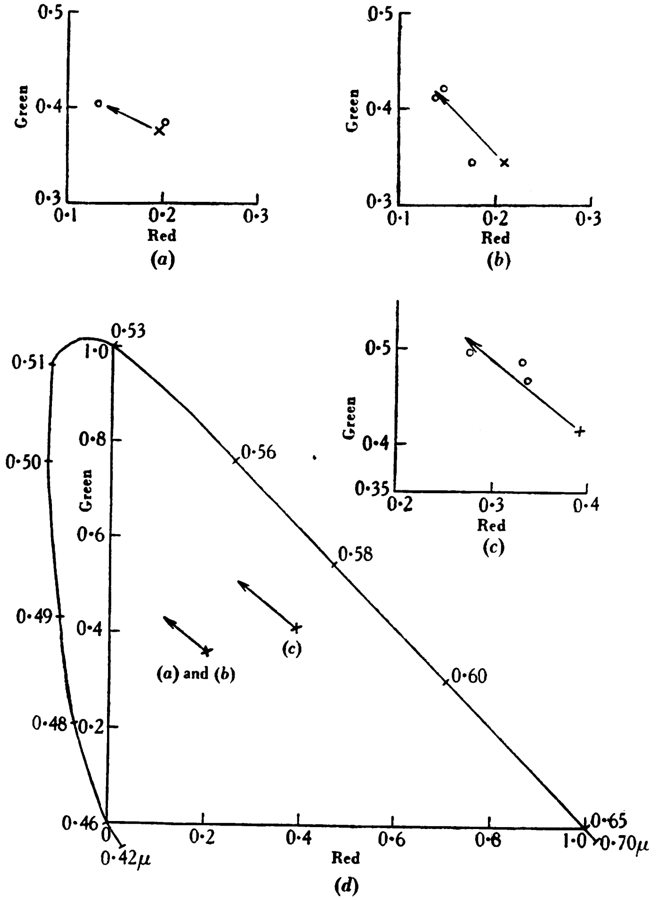

Fig. 1. Diagrams to show the effect of the colour match breakdown on the position of the white point in the colour triangle. (*a*) Shows results of Table I; (*b*) results of Table II; (*c*) results of Table III; (*d*) indicates the general tendency as derived from the mean of (*a*) and (*b*) and from (*c*). The change in the white point is shown relative to the spectral locus. × Shows white point as measured with the eye in its normal state. o Shows white point when the eye is in its "colour match breakdown" state.

in which the white point has moved after adaptation, as derived from (*a*) and (*b*), and, separately, that derived from (*c*). It is not, of course, at all certain that the locus of the white point is a straight line.

It is interesting to note that the white point has moved away from the purple side of the triangle towards the blue-green, and the question immediately arises as to whether this is evidence that the phenomenon is due to the bleaching of the visual purple. Assuming visual purple to be the initial light-sensitive substance, then after it is bleached it is presumably inactive and could have no effect on the shape of the response curves. A simple bleaching of the material is thus hardly a sufficient explanation of all the observations. It is necessary to assume a partial bleaching, and that the light-sensitive substance, in changing its absorption characteristics, does not lose its sensitivity to light. Whether this is consistent with the laws of photochemistry, the author is not in a position to decide, but the data are at least suggestive that a bleaching of a purple substance is in progress.

APPENDIX

Adaptation and intensity discrimination

The effect of adaptation on intensity discrimination has recently been the subject of two papers, one by the author [1935] giving some experimental results and their theoretical interpretation, and the other by Hecht [1936] attempting to reverse this interpretation. The author cannot, however, accept Hecht's arguments, for the reasons given below.

Two series of experiments were reported. An intensity discrimination observation was performed, first when viewing a test patch of intensity I to determine the just noticeable increment ΔI, and then repeating the observation after the eye had been adapted to a high intensity field of brightness I_a. In one series of experiments, the value of ΔI was determined using different adaptation intensities but with a constant value of I. In the second series, the test patch intensity was varied and I_a maintained at a constant level.

In the first series, it was found that ΔI was very nearly constant for a wide range of adaptation intensities, while in the second, ΔI was found to be directly proportional to I. In other words, while the value of ΔI was, within limits, independent of the state of adaptation, it was always found to bear a constant relation to the magnitude of the test patch intensity.

It appeared to the author that this result conflicted directly with Hecht's photochemical theory of intensity discrimination, but this conclusion has been questioned by Hecht. The first experiment he explains on the assumption that within the range of adaptation intensities used, the state of adaptation was practically unchanged, and for the second experiment he applies formulæ derived from his hypothetical photochemical adaptation mechanism to prove that $\Delta I/I$ should be constant under the experimental conditions used.

Both these statements are in error, but the second will be dealt with first as it involves a directly demonstrable misapplication of his formulæ. He derived the following equation for $\Delta I/I$:

$$\Delta I/I = c/x^n, \quad \text{[Hecht]} \qquad \ldots\ldots(5)$$

where c is a constant and x is the concentration of the photo-products in the retina, when the eye is adapted to the intensity I. This equation was derived on the explicit assumption that the concentration x was produced by adaptation to the intensity I, and it only applies and may only be used in cases in which I and x are related in this manner. Hecht, however, deduced that after adaptation to a constant intensity I_a, the concentration x_a, and hence $c/x_a{}^n$, would be constant, and then claimed that $\Delta I/I$ would be constant for any value of I. This is quite wrong. All that can really be proved from (5), when x_a is constant, is that $\Delta I_a/I_a$ will also be constant, which, since I_a will have to be constant, is obvious.

To test Hecht's theory, the correct equation of his to apply to the case in question is his equation (4), namely,

$$(dx/dt)_{\Delta I} = k_1 . \Delta I \, (a-x)^m, \quad \text{[Hecht]} \qquad \ldots\ldots(4).$$

In the experiment carried out with the eye in a given state of adaptation, x will be constant, and for a just noticeable difference Hecht postulates that $(dx/dt)_{\Delta I}$ has to be constant; equation (4) is then only satisfied if ΔI is constant; that is to say, however the test patch intensity may be altered, the value of ΔI should remain unchanged. This was precisely the result that had been anticipated by the author, but exactly the opposite was found. Experiment proved that $\Delta I/I$, and not ΔI, was the constant quantity when the adaptation was kept steady and the test patch varied. We are thus forced to the original conclusion that the supposed relation between adaptation and intensity discrimination, inherent in Hecht's theory, is unfounded.

In the other experiment, the test patch was maintained at a constant value, while the adaptation level was varied. In this case it was found that ΔI now remained practically unchanged. Hecht explains this by concluding that between the adaptation limits tested, namely 1000 and 40,000 photons, the state of adaptation of the eye is practically unaltered. The evidence he gives to support this is (*a*) that $\Delta I/I$ is constant within these limits, (*b*) visual acuity is constant, and (*c*) critical fusion frequency is constant. The constancy of $\Delta I/I$ proves nothing about adaptation unless we accept Hecht's theory; that is to say, if we assume what we have to prove, we can prove what we have assumed. As regards (*b*) and (*c*), so far as the author is aware, there is no evidence to show that either visual acuity or critical frequency is a direct measure of adaptation, and while there might be some indirect relation to the photochemical concentration in the retina, this would have to be established before the data could be regarded as relevant to the present problem. Adaptation is essentially the mechanism by which the visual response is reduced as the intensity of the stimulus is increased, and the proper measure of the adaptation level is given by the apparent brightness of some reference test patch. An elementary experiment will demonstrate that there is a very great difference in the state of adaptation after the retina has been illuminated to an intensity of 1000 photons compared to that when an intensity of 40,000 photons is used. If a test patch of, say, 100 photons is viewed in turn after adaptation to these two intensities, the difference in the apparent brightness of the patch in the two cases will be very marked. From the author's binocular matching experiments, it appears that, for his own eye, the sensitivities in the two cases are in the ratio of about 40 : 1. But using entirely impartial evidence, the threshold brightness in the two cases as determined by Nutting [1920] gives a sensitivity ratio of approximately 30 : 1. No doubt whatever can exist that a very considerable change indeed takes place in the adaptation level of the retina, and there is therefore no escape from the conclusion that, from the evidence of the author's experiments, adaptation and intensity discrimination involve fundamentally distinct visual mechanisms. Hecht's theory of intensity discrimination cannot be accepted, since it does not fit the facts.

SUMMARY

The breakdown in a colour match between yellow and a mixture of red and green after the eye is adapted to an intensity above 15,000 photons has been measured and the measurements extended to other test colours. By basing the trichromatic coefficients on units based on matches of monochromatic radiations, changes occurring as a result of changes in the receptor processes can be separated from alterations in the absorbing media through which the light has to pass before reaching the retina. It is found that the breakdown is due to the receptor process itself, and the effect on the white point suggests that it may be due to

the bleaching of the visual purple. In an appendix, the author replies to a recent criticism by Hecht of the author's interpretation of some results obtained on intensity discrimination. It is shown that Hecht has misapplied the formulæ of his photochemical adaptation mechanism, and the author's contention that adaptation and intensity discrimination are independent and involve fundamentally distinct mechanisms is confirmed.

In conclusion, the author desires to express his thanks to Mr J. H. Nelson for his assistance in recording the observations, and to the Medical Research Council for their financial assistance.

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