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THE SPACE-THRESHOLD OF COLOURS AND ITS DEPENDENCE UPON CONTRAST

FIRST ARTICLE

By

W. B. LANE, M.A.

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I.
INTRODUCTORY.

In an article by Mr. J. O. Quantz, B.A., published in the American Journal of Psychology, Vol. vii., No. 1, the dependence of size estimation upon colour is discussed. This problem naturally suggested a converse inquiry into the dependence of colour perception upon size. But colours are not ordinarily seen in complete isolation. There is always an environment which exercises, through contrast, a decisive influence upon the perception of colour. It therefore appeared desirable not merely to investigate the question under conditions of contrast, which in some form was unavoidable, but to examine into the specific nature of the relation between particular kinds of contrast, *e.g.*, pure colour contrast and magnitude of coloured surface.

The field of optical contrast is of great extent and includes a considerable variety of distinguishable influences. It will be necessary to discriminate between them both for the purpose of investigating the bearing of contrast upon the problem in hand, and in order to define the particular kind of contrast with which we are concerned. Optical contrast has been divided into successive and simultaneous contrast. The former, successive contrast, is identical with th phenomenon of after-images. If one turns away after looking at a dark surface on a bright ground, one will have a series of alternating positive and negative after-images, in the latter of which the ground will appear dark and the dark surface bright. This inversion of the relationship between surface and ground in the negative after-image is a case of so-called successive contrast. That part of the object of consciousness which at one moment was bright appears at a subsequent moment dark, and the dark portion appears bright, a fact which seems to indicate that the relationship between the parts of the after-images in respect to brightness is inversely dependent upon the same relationship as it exists between the parts of the preceding original images. Helmholtz in his *Physiological Optics* states the law thus: "After looking at a colour *A* of moderate intensity then look at another *B*. If the after-impression is not sufficient to produce a positive image it produces a negative image of *A* on *B*. The parts of *B* which are in the same place as *A* are dimmed. If *A* and *B* are of the same tone then *B* is rendered more whitish, if they are complementary *A*'s saturation increases. If *B* is between *A* and its complementary it passes for a neighbouring tone which is further from *A* and nearer its complementary. Otherwise *B* becomes dark as much as *A* becomes more bright." It was from this kind of contrast that we sought to free our experiments as far as possible.

Simultaneous optical contrast embraces all, and more than all the phenomena of contrast whose connection with the space threshold of colour I seek to trace in this paper. It includes all such phenomena as the modification in apparent size, colour, etc., which one visible surface exerts upon our visual impression of another surface at the moment of that impression. There may be several kinds of modifying influence by which to classify the facts of simultaneous contrast. It may consist in (*a*) modification of the apparent size of the surface (extension contrast), (*b*) modification of the apparent brightness of the surface (brightness or intensity contrast), (*c*) modification of the saturation in the case of a coloured surface (saturation contrast), (*d*) modification of the colour tone of the surface (colour contrast), or (*e*) modification in the emotional tone accompanying the perception of the surfaces.* In our usual experience these kinds of contrast appear for the most part in combination, but they are for all that quite distinct, and, in scientific abstraction, separable features of ordinary contrast effects. The only one likely to be obscure is saturation contrast, to which alone therefore I will briefly refer. By saturation as distinct from colour tone and brightness is meant the degree of colour quality as compared with the absence of the same. By colour tone, on the other hand, is meant the degree of transition in a closed manifoldness of

* For a discrimination of the various kinds of simultaneous optical contrast see American Journal of Psychology, Vol. iv., No. 4: "Some Effects of Contrast," by Dr. A. Kirschmann, and the same author's inaugural dissertation, "Ueber die quantitativen Verhältnisse des simultanen Helligkeits- und Farben-Contrastes," in Philosophische Studien, Bd. vi., p. 417.

colour wherein the tone is determined, not by relation to the absence of colour quality, but by relation to other colour qualities of the same manifoldness. For example, green, red, orange, etc., are transitions in a closed series of colour which begins and ends in colour, but between each of these, taken separately, and the disappearance of colour altogether there is a series of transitions which rise from the zero point of colour quality to the highest possible degree of it. These latter transitions are called degrees of saturation of the particular colour, whether it be green, red, orange, or any one of the infinite possible transitions in the closed colour manifold. In other words if we represent the transitions of colour tones graphically as a circle we must convert our two-dimensional circle into a geometrical figure of three dimensions in order to make it also represent the manifold of possible saturations. That saturation, and therefore saturation contrast, are not mere matters of speculative formula, which can practically be neglected in considering the possible contingent influences to be eliminated in an exact examination of colour contrast, is shown by the fact that it is possible to vary the saturation of coloured surfaces without changing the light intensity or colour tone. Dr. Kirschmann has succeeded in doing so by means of colour discs. For a description of the means employed I refer to his article "Colour Saturation and its Quantitative Relations" (American Journal of Psychology, Vol. vii., No. 3), in which he has given a preliminary account of the subject. For my purposes it suffices to point out that saturation contrast, which means contrast between different degrees of saturation, all of equal light intensity and the same colour, is a possible contingency which had to be taken account of in the prosecution of our contrast study.

Since in any ordinary case of colour contrast there are these different influences at work, it was necessary to disentangle them as far as possible and to confine our investigation to one alone. Accordingly in our inquiry we sought to limit ourselves mainly, if not absolutely, to colour contrast, by which is meant contrast of colour tone, not in the ordinary careless use of the term but in its strict significance as distinguished from saturation and intensity. Our problem then in its bearing on contrast phenomena is mainly to examine the relation which holds between colour contrast and the magnitude of coloured surface in the initial stages of the perception of a coloured object. By magnitude is meant not the absolute size of the surface but the visual size, if we may so speak, that is, the size as relative to the perceiving eye, which the absolute size of the surface and its distance from the eye conjointly determine. The visual size of an object is measured by the angle which that object subtends at the centre of the pupil of the eye, an angle which is named the visual angle and which for any object of constant magnitude varies with the distance from the eye. Of course for every object at any distance there are as many visual angles as it has different diagonals and diameters. If the visual angle (selecting for the purpose either a diagonal or a diameter angle) at which a coloured surface is first distinguishable in its proper colour tone may be called the spatial threshold of that colour, we define our present problem as an inquiry into the spatial threshold of colours, especially when those colours are subjected to the contrast influence of other colours. Incidental to the examination of this problem will come naturally also an investigation into the influence of colour contrast upon two other possible spatial thresholds, viz., (1) the threshold at which a coloured surface appears first as light, and (2) the threshold at which such a surface appears coloured though not in its proper colour tone. These will form subordinate problems whose elucidation will necessarily take place concurrently with that of the main problem. For it has long been well known that a colour, whether under the contrast influence of other colours or not, does not retain its characteristic colour quality at very small visual angles, nor does it, by the gradual enlargement of the visual angle from zero, emerge at first upon the vision fully formed in its proper tone. On the contrary almost all colours lose their special colour quality at determinable small visual angles and appear either only as light or as some other colour. A very familiar example is the greyish appearance of a distant autumnal hillside, clad in leaves which are beginning to change their tints. At a distance of three or four miles it is not only impossible to distinguish the colour qualities of the variously tinted surfaces, which on closer inspection are seen to be massed into a mosaic of peculiar beauty, but their joint effect at a distance is frequently that of a characterless russet grey. The reason is that each of the colour surfaces subtends so small a visual angle that its stimulus is below the threshold of perceptibility for that colour; and while at nearer view they would make good to the spectator their many differences of colouring, yet in the greater distance the purple, orange, yellow, red, green, brown, with their many shades and hues to be found in such a landscape, are indistinguishably blended in one poorly saturated reddish colour, or even reduced to a plain colourless grey. Another illustration of the same fact is our inability to distinguish the violet colour of a pansy at a distance which is not great enough to render the object itself quite invisible. On withdrawal of the spectator to sufficient distance the flower becomes indistinguishable from a dark grey or black spot and at still greater distance disappears entirely. When we approach again it gradually becomes visible, first as a point of grey light and then as coloured though not yet violet. Still nearer the violet character of its colouring is distinctly perceptible. From these familiar examples the fact is illustrated that most coloured objects have three different stages of perceptibility which are dependent upon their spatial relations to the eye of the percipient. The first is when they are merely visible but without colour at all; the second when they are seen to be possessed of colour though not the proper colour; and the third when they become visible in their correct colour quality. The exact delimitation so far as possible of these three thresholds of colourless, chromatic and characteristically coloured light for all the variety of colour presented by the spectrum is the aim of the present paper. The problem with which we started was to determine the last of the above, but in dealing with it the question of the two former naturally arose. In the perception of a coloured object the lower thresholds must be passed through before the third is reached, and therefore they also properly fall within the scope of this paper and were investigated at the same time as the main problem.

I do not mean to imply that every colour will have three thresholds absolutely distinct from one another without the possibility of a coincidence of any two of them or of all three. There are many facts apart from those which have made their appearance in the course of our experimental treatment of the problem which would bear strong evidence against such an assumption. It has perhaps frequently been noticed that a red light, for instance the port light of a vessel at sea or the danger light of a train, remains visible as red almost or quite as long as it is visible at all, which goes to indicate that its achromatic, chromatic and characteristic colour thresholds as distinguished above are not separated but coincident. Our experiments have corroborated such observations, showing in a more exact and quantitative way that red is a colour which does not easily or at smallest surface sizes lose its colour quality, but is for the most part distinguishable as red just as long as it can be discerned at all in the diminution of its extension. For most colours, however, it will be found that the three stages of discernment are distinct, and consequently will require separate examination.

II.

HISTORY OF THE PROBLEM.

The phenomenon of a space threshold of colour was noticed in the early history of physiological and psychological science although it did not receive careful investigation. It was noted and passed by without any thorough inquiry into the details or quantitative relations of the problem. Such cursory treatment practically amounted to nothing more than calling attention to the existence of a subject that demanded scientific investigation. Within recent years, however, some attempts at explanation have been made which yet, as we shall see, have not completely satisfied the conditions of such an inquiry.

As early as 1823, the dependence of perception of colour upon the visual angle of the coloured surface was noticed by Purkinje.* He called attention to the fact that both intensity and visual angle play an important rôle in the perception of colour. "Sensibilitas oculi in specificam coloris cuiusdam qualitatem ad diversas distantias et sub certis gradibus luminis examinari poterit, nam notum est qualitatem illam colorum in objectis affatim minutis ad justas distantias evanescere."†

Plateau was the first, perhaps, who noticed and recorded the fact that colours disappear as colour at very small visual angles of the coloured surface.‡ However, he made no further use of his observation, and did not attempt any detailed inquiry into the subject. In fact none of the early investigators sought to determine with any exactitude the nature of the relationship which they observed between the visual size of a coloured object and its perceptibility as colour, and, so far as I can find, no fruitful advantage was taken of the fact which these early scientists had noted. Not until comparatively recent times, by Von Wittich and Aubert, was any attempt made to determine quantitatively the relation of colour perception to the size of the coloured surface.

* Commentatio de examine organi visus, etc. Breslau, 1823. (P. 15.)
† Quoted by Aubert in his *Physiologische Optik*.
‡ Poggendorff's Annalen, Bd. 20, 1830. (P. 327.)

Von Wittich records in the Königsberg medical Year Book some interesting experiments made to ascertain what were the smallest visual angles at which the several colours could be perceived, either at all and in any form, or as of their proper quality. The results obtained were twofold, the objects being viewed momentarily on the one hand and on the other continuously for sufficient time to render possible a secure judgment. The following tables give his results which will subsequently be used for comparison.

Black Ground.

Colour	Momentary view				Continuous view			
	Visible		Coloured		Visible		Coloured	
	′	″	′	″	′	″	′	″
Red	1	23	1	58	1	4	1	4
Orange	1	4	1	32	1	4	1	4
Yellow orange	1	9	1	32	1	14	1	14
Yellow	1	23	1	23	1	4	1	4
Pure green	1	23	1	43	1	4	1	43
Dark green	2	17	6	53	2	17	3	16
Pure blue	1	14	2	17	1	14	1	43
Dark blue	2	17	7	38	1	58	3	26
Rose	1	14	2	17	1	32	1	32
Violet	1	43	6	53	3	26	3	26

White Ground.

Colour	Momentary view				Continuous view			
	Visible		Coloured		Visible		Coloured	
	′	″	′	″	′	″	′	″
Red	1	23	6	53	1	9	2	50
Orange	1	43	3	8	1	4	1	32
Yellow orange	2	17	5	43	2	17	2	50
Yellow	6	53	6	53	3	26	3	26
Pure green	2	17	3	26	1	43	1	43
Dark green	1	23	13	46	13	46	13	46
Pure blue	1	23	4	35	1	9	1 (2	43 17)
Dark blue	1	23	5	17	1	4	2	17
Rose	1	43	4	35	1	9	2	50
Violet	1	32	13	46	1	9	5	43

As Plateau had previously seen, when he said that coloured objects at small visual angles appear as a scarcely perceptible cloud, Von Wittich noticed that colours at very small visual angles lose their characteristic tone and appear either as quite colourless light or of some other colour tone. In his experiments tabulated above he therefore investigated what might be called two space-thresholds of colour perceptibility, the one where the surface is barely visible at all and in no case correctly coloured, the other where it is seen coloured. In short he has treated what we have already distinguished as the achromatic space-threshold and the chromatic space-threshold, though he has not made the distinction between the merely chromatic and the proper colour threshold (or what we have designated the characteristic colour threshold), wherein the coloured surface is not only seen to be coloured but, what is quite different in many cases, seen coloured as it actually is.

The means which Von Wittich employed in his investigations were small coloured squares which he moved to and from the observer by gradual transition until the different threshold points were reached. The distances from the observer and the absolute size of the coloured objects being known, it was a matter of easy calculation to interpret the observations in the form of visual angles.

Von Wittich in his work noticed and emphasized a fact which was disclosed also in the course of our experiments, that when an object becomes barely visible it becomes so only momentarily and will appear and disappear again in the most capricious manner. Especially is this the case in a darkened room where the observer has no distracting light to employ his attention except that which is looked for from the object. Then the point of light will break into the field of vision from the most unexpected quarter, will dwell for scarcely a moment, then suddenly disappear to appear again in the vision field in some other place. Von Wittich also noticed the same peculiarity of momentary visibility in the emergence of the colour sensation. He has recorded the observation that in the first stages of colour perception, the colour, as before in the case of mere light, is seen only intermittently, and that too only in the case of movement either of the eyes or of the object itself. He gives a very interesting example of this necessity of movement in his experiment with coloured fibres, some of which were fixed at a certain distance and some were in movement. The moving fibres were seen as coloured from a greater distance than those at rest, thus indicating that movement certainly plays an important rôle in the perceptibility of colours. We have found frequent confirmation of this observation of Von Wittich's in the course of our experiments. It was a common experience for our observers, after having affirmed that they saw the light point coloured, to recall the affirmation because the colour had instantly changed again into the point of colourless light And the reason was not far to seek. In their endeavour to identify the colour just emerging they had fastened their eyes upon it too fixedly, with the consequence that the colour quickly disappeared. As soon as the fixedness of their gaze relaxed and the eye was permitted to perform those slight involuntary movements, which always accompany a clear visual perception, the colour reappeared forthwith.

Von Wittich did not fail to notice the fact that a considerable difference in the space-thresholds of colours obtains, according as those colours are viewed upon a black or upon a white ground. An examination of his tabulated results given above shows that the colours he employed have usually somewhat higher space-thresholds against a white than against a black ground. There are some notable exceptions, as, for example, dark blue, which on a white ground by momentary inspection is first visible at a visual angle of 1′ 23″, and first seen as coloured at a visual angle of 5′ 17″; on continuous view it is first visible at a visual angle of 1′ 4″, and first seen coloured at 2′ 17″. On a black ground momentarily viewed it is first visible at 2′ 17″ and coloured at 7′ 38″, steadily viewed it is first visible at 1′ 58″ and coloured at 3′ 26″. There are other incomplete exceptions such as violet which on a white ground is seen uncoloured earlier than on a dark ground, although the discernment of it as coloured comes at a very much greater visual angle for white ground than for dark. The probable explanation of these exceptions is to be found, it seems to me, in the fact that the black which Von Wittich employed was black cardboard, by no means a good specimen of non-reflecting surface. As compared with the black of a good velvet, black cardboard is grey. This goes to show that surfaces which we call black are only relatively black and consequently that a haphazard choice of them for employment as black grounds in experimental work might easily lead to a condition where the ground actually reflected scarcely less light than some of the colour pigments. It is likely that something of the kind has been the case in Von Wittich's experiments. The violet and blue pigments which he used were pigments which relatively to the other colours reflected very little light and consequently were much more akin to black than the rest. The contrast of brightness intensities between ground and pigment in the case of these two would be much less when the ground was black cardboard than when it was white, whereas with the brighter colours the exact opposite would probably occur. We should therefore naturally expect that violet and blue would prove themselves at variance with the other pigments in regard to their colour thresholds on white and black grounds, that they would in fact have lower thresholds on the white ground than on the black, while the others had lower thresholds on the black ground. On the other hand, had the black ground used been not merely a comparative black, such as cardboard or even velvet, but actually a surface reflecting no light whatever, then it is possible that the blue and violet would have followed the same rule as the other pigments.

Aubert, in the work which he has done, so far as it bears upon the problem of the space threshold of colours has largely followed in the footsteps of Von Wittich. He has indeed refined somewhat upon the means employed but in the total outcome he has made very little advance. He employed coloured squares of two millimetres in diameter placed equidistantly from the spectator in diffuse but clear daylight. The observer withdrew to a distance at which the squares could no more be seen. He then gradually approached to such positions as would respectively enable him just to see the objects as uncoloured, advanced further until he could see them as coloured, whether properly or not, and still further until he saw them in their proper tones of colour.* By measuring the distances of the observer's several successive positions he had the material for a calculation of the visual angles which coloured square surfaces must subtend in order to be, first, seen at all, secondly, seen coloured and thirdly, seen coloured correctly. In order to rest the vision Aubert also used in his experiments darkened tubes for the eyes with a mask to close off the diffuse daylight which illuminated the colour pigments.†

The results which Aubert attained were considerably different from those of Von Wittich. This difference he ascribes to three

*Abhandlungen der schlesischen Gesellschaft (Breslau, 1861), and Physiologische Optik.

†Aubert, Physiologie der Netzhaut, p. 1[illegible]5.

main causes, (1) the place of the illumination, (2) the pigments used and (3) the subjective uncertainty concerning the extreme limits which can be set to perceptibility. He found* that orange appears coloured from the first, at 39″ as red, at 59″ as orange; red on a black ground at 59″ is seen as red, while on a white ground at 59″ it is dark, almost black, and becomes coloured at 1′ 43″; ultramarine blue on a black ground at 1′ 14″ is grey, at 4′ 17″ blue, while on a white ground at 1′ 8″ it is black and only becomes visible as blue at 5′ 43″; bright blue and bright green appear at 1′ 8″ both equally grey (light grey on black and dark grey on white ground), while they become discernible as blue and green at about 2′. The following further results are taken from some notes on Aubert's *Physiologie der Netzhaut*:—Rose on a black ground appears grey at 39″, at 59″ yellow, at 1′ 8″ golden yellow, at 1′ 23″ reddish yellow, at 3′ 47″ rose; dark brown at 1′ 8″ is seen as fawn-coloured: green at 1′ 8″ is bluish at 1′ 49″ green; on a white ground bright blue is seen as black at 1′ 8″ and at 1′ 49″ as dark blue. Orange is first seen coloured at 35″; red is first seen coloured at 39″, green at 44″, blue at 2′ 7″, yellow at 41″.

From the above figures it will be plainly seen that the discrepancies which Aubert himself noticed between his own and Von Wittich's results and between his own at different times are not inconsiderable, so far at least as the absolute numerical values of the visual angles are concerned. Whether the relative values among the various colours show any similarity or regularity as between the results of the two investigators we are unable to pronounce upon, because the colour list which Aubert used and that of Von Wittich have few points in common. Had they both employed the same set of colours it might have been shown that although there were considerable discrepancies in the actual figures given by the two for any one colour, yet the mutual relationships among the various colours were fairly constant.

Aubert has made one material advance upon Von Wittich's work in the investigation of this problem. He has contributed to the more definite distinction of the mere chromatic from the characteristic space threshold. Von Wittich combined the two in the records of his observations although he did not fail to notice the existence of the distinction. Aubert not only definitely enunciates the distinction, but also gives it a quantitative expression and

*Aubert, Physiologische Optik, p. 537.

notes the visual angles of the colours quite as carefully when they are first seen coloured, though incorrectly coloured, as when they are seen in their proper tone.

The work which Von Wittich and Aubert have done upon this problem of the space-thresholds of colour perceptibility cannot but be seen to be incomplete in method and results. Its deficiencies, however, are largely those which attend pioneer efforts in any line of work. For them the question arose as a curious fact of no small interest in the midst of other problems more immediately engrossing, with the inevitable consequence that the investigation was not completely carried out in all its various and obvious divisions. The subject which they dealt with in a somewhat incomplete way is capable of considerable extension. They recognized in some degree the influence which contrasting surfaces have upon the perceptibility of colours. Thus they took into account the difference of white and black surfaces in this regard, examining their colours when subject to the contrasting influence of black and white grounds. But although it is quite as frequent in every-day experience for colours to be seen upon backgrounds of other colours as upon the colourless grounds of white and black, yet it never seems to have occurred to these early investigators to examine the perceptibility of colours under the ordinary influences of colour contrast. It is not improbable that colour contrast would introduce quite as considerable variations into their results as did the contrast with white and black. And indeed our own experiments have confirmed this *primâ facie* probability as will be seen subsequently in the exposition of our results.

Apart from the omission of Von Wittich and Aubert to extend their investigation to the full limits of the problem we cannot fail to notice the unsatisfactoriness of their method even within the circumscribed sphere of their inquiry. What precautions did they adopt to insure with fair reliability that the thresholds which they found for the perception of colour were really assignable to the colour perception *per se* rather than to colour perception aided or retarded by some other accessory conditions? For example, can we be sure that the threshold of 39″, at which Aubert finds that orange is seen as red, is really the chromatic threshold of orange, unaffected by contrast of light? It appears to be quite probable that this result is in part due to the influence of the contrasting intensities of the colour pigment used and its surroundings. It is indeed true that these investigators do not attempt to maintain that their results indicate anything but the perceptibility of colours when seen upon certain specific grounds, namely black and white. Such results may have served their purpose and observations on that basis may be of considerable practical value. But I must insist that the mere fact of their performing their experiments under certain conditions of contrast is far from being a recognition or discovery of the exact part which contrast plays in the matter. Again it appears to me to be scientifically desirable to remove in some way if possible the contribution which intensity contrast brings to the results recorded, and to isolate the conditions that produce pure colour perception. Neither Von Wittich nor Aubert made any attempt to separate the factors that entered into the colour perceptions which they examined. I do not mean to suggest that it would be possible to remove the factor of light intensity altogether from the field in order to get at the perception of colour pure and simple. This would be to eliminate colour itself, because every colour must have a certain intensity as light. But it is not necessary to do this in order to secure the separation of the two factors. What is necessary is to prevent inequality of light intensities and thus to remove the disturbing influence of light contrast. This would be effected if it were possible to equalize the intensities of ground and colour.

It is very likely that neglect to eliminate the influence of light contrast between the pigment surfaces examined and the grounds on which they were seen contributed largely to the disagreement which Aubert finds between his own results and those of Von Wittich and also to the discrepancies which occur in his own observations; not that they are altogether due or even mainly due to this cause, but such an influence must indisputably have had a great effect in modifying results, and in the nature of the case must have been brought into play in different degrees not only in Von Wittich's experiments, as compared with Aubert's, but likewise in the various examinations of each pigment made by either of them. This is plain from the fact that scarcely any two pigment surfaces have exactly the same light-reflecting power. And the same is true of the black and white surfaces. It can be photometrically shown that some surfaces which we call black reflect many times more light than others which we likewise call black. The terms black and white are in fact elastic in their significance, each including an indefinite number of surfaces of varying degrees of light-reflecting power.* Since such is the case it becomes plain that the quantitative relation between ground and colour in respect of light intensity must vary not only according to the blacks and whites used for grounds but also according to the several colours examined; and not only will this variation depend upon the essential differences between the pigment colours, such as green, red, etc., in light-reflecting power, but it will exist no less concomitantly with the difference in the pigment paper employed for each colour by two or more experimenters, or by any one of them at different times Accordingly, the observations of Von Wittich and Aubert may be expected to show greater discrepancies for some colours than for others, and for some tones of the same colour than for other tones. In this manner the threshold differences among the various colours would be exaggerated. Moreover the natural divergencies for the same colours which arise from varying individual sensibility among observers would be accentuated by the use of slightly different pigments, which would render them unduly and in indeterminable degrees greater or less than if exactly the same conditions of light-intensity-contrast obtained. It is therefore apparent that from this uncertain variable, arising from contrast of light intensities not being converted into a contrast by equal distribution to all colours, a means was afforded for the entrance of considerable discrepancies into the results.

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*Dr. Kirschmann has made interesting experiments which illustrate this statement very well. He records them in his article "Ein photometrisches Apparat zu psychophysischen Zwecken" published in vol. v. of Wundt's Philosophische Studien. He compares photometrically various blacks with a standard white--

I. Paris Black:

(1) in lamplight (petroleum) $\frac{1}{59 \cdot 9}$ of the intensity of white.

(2) in gaslight $\frac{1}{58 \cdot 2}$ of the intensity of white.

(3) in diffuse daylight $\frac{1}{57 \cdot 2}$ of the intensity of white.

II. China Ink:

(1) lamplight $\frac{1}{23 \cdot 6}$ of white.

(2) diffuse daylight $\frac{1}{20 \cdot 2}$ of white.

III. Graphite (Faber BB):

(1) lamplight $\frac{1}{8 \cdot 6}$ of white.

(2) diffuse daylight $\frac{1}{8 \cdot 9}$ of white.

IV. Graphite (Faber B):

(1) lamplight $\frac{1}{6 \cdot 2}$ of white,

(2) diffuse daylight $\frac{1}{6 \cdot 9}$ of white.

This goes to show the photometric variability in what are ordinarily accepted as good blacks—a range broadly speaking from $\frac{1}{60}$ to $\frac{1}{6}$ of the white chosen for standard of comparison.

From another standpoint their method of investigation appears to be unsatisfactory and to give results of merely individual validity. It seems that both Aubert and Von Wittich employed ordinary pigment papers, without making any attempt at controlling or checking some other obvious errors thereby introduced. For such pigments when examined under the spectroscope are found to contain not only the particular kind of coloured light under the name of which each passes, but also in varying degrees many other spectral colours. The blue which we see in a blue pigment paper is for the most part merely a predominant element in a mixture of many similar colour elements. It is not necessary even that there should be any actual rays of the specific kind which gives its name to the pigment paper. Some violet pigments do not emit any violet rays whatsoever, but only blue and red. Frequently a pigment gets its colour not because of the predominant presence of rays of that colour but because of the weakening or absence of its complementary in the assemblage of colour elements. This is chiefly the case with the best yellows, which derive their specific quality largely from the attenuation of the blue rays. It is plain that unless some means are employed to diminish these foreign colour elements so as to reach a comparatively pure colour, we are not sure that the results obtained by the use of these mixed colours are attributable to one rather than to several co-operating colour elements. In fact the conclusions of Von Wittich and Aubert are entirely inapplicable to pure colours and only held good of specific adulterated specimens, the colour pigments which they chose to operate upon. This fact, as Aubert has indicated, would account partly for some of the differences which occurred between his results and those of Von Wittich, for the pigments they used as representative of the various colours would differ in the degree of their colour saturation and in freedom from admixture of foreign elements.

It is a conspicuous deficiency in Aubert's treatment of this problem that he picks up colours at haphazard and in a popular way, without any attempt to make his examination cover the complete field. We find him, as well as Von Wittich, including in his list such specimens of unscientific commercialism as brown or fawn and omitting from it such important colours as violet (which Von Wittich, however, includes) and purple. Brown and fawn-colour so far as they are colours at all, are nothing but more or less liberal saturations of the standard colours. Some browns are merely reds of comparatively poor saturation and light intensity; others are yellows. An interesting experiment is recorded by Dr. Kirschmann* which brings out this fact. It consisted in endeavouring to detect brown surfaces by looking through tubes blackened on the inside and of aperture amounting to about one square inch. In each case browns were judged to be red or orange or yellow, and thus it was shown that they are not simple colour tones, such as red, but that they obtain their peculiar colour characteristic for our vision by such accessory influences as contrast.

We have made some experiments under very much the same conditions as Aubert and Von Wittich, namely, without taking care to eliminate intensity contrast, and using ordinary pigments with daylight illumination. Our sole object was to institute a comparison with Aubert's and Von Wittich's figures. The accompanying table contains the results of our observations when the colours were seen on a black ground. The angular values are calculated on the basis of the diameter (not the diagonal) of the square opening in the brass diaphragm, since apparently Aubert's and Von Wittich's calculations were made upon the the same basis. In our other work, for greater convenience in the adjustment of our apparatus, we have adopted the diagonal basis.

Colours.	Seen first as light.		Seen first coloured (chromatic threshold).		Seen correctly coloured.	
	′	″	′	″	′	″
Purple		52.98	1	30.3	1	58.66
Red		55.56		55 56		55.56
Orange		48.64		48.64	3	56.78
Yellow	1	14	2	39.52	2	39.52
Yellow-green		42.84	2	39.44	2	58.86
Green		46.9	2	10.48	4	2.56
Blue-green		48.4	2	9.88	6	33.14
Blue		53.04	3	15.7	4	30.48
Violet		58.12	4	3.58	5	41.76
Grey	1	17	6	19.72	....	

It will be noted, as was to be expected, that our results differ considerably from those of either Von Wittich or Aubert. It would indeed have been strange if they had coincided in all points because

* "Colour Saturation and its Quantitative Relations," American Journal of Psychology, Vol. vii., p. 391 (1896).

no precautions were used to rule out the many modifying accessory influences which we have spoken of above, except perhaps that care was taken to secure a very close approximation to an absolute black ground and thus to eliminate in part one variable in the undetermined disturbance introduced by intensity contrast. The observation tube was continued to the brass diaphragm by means of a pasteboard annex, which fitted tightly, without any crevices to admit light either at the point of junction with the observation tube or where it joined the plane on which the diaphragm was fastened. The necessary openings to allow of free movement of the sliding plate of the diaphragm were completely obscured by pendent velvets attached to the annex tube. The annex was lined with black velvet and the surface of the brass diaphragm was painted black. By these means was secured a very good specimen of black upon the ground within which the colours were seen.

In the main our results show a lower achromatic threshold than Von Wittich's, and even than Aubert's with a few exceptions. But on the other hand the chromatic and the characteristic colour thresholds in our observations are somewhat higher.

This regularity of disagreement in colour thresholds may have been due to one or both of two causes. In the first place Aubert and Von Wittich varied the visual angles by employing the method of departure and gradual approach, and this of course implied that the observer knew beforehand what colours to expect at the extreme distance. They record no precautions used to obviate this influence, and the presumption is that they took none. But surely such a mental preparation would have a tendency to bring the characteristic colour thresholds below what they should be if the observer had no means of forming an opinion beforehand of what to expect. It would even have the same influence on the chromatic thresholds, at least when, after a few experiments, the observer would have become familiar with the transitional colours through which each colour passes from the achromatic to the characteristic threshold. Secondly, Aubert employed fewer colours than we did. He used about five or six different tones, among which the observer had to choose, whereas in our experiments under daylight illumination ten different colours were examined. The difficulty in deciding accurately the characteristic threshold would increase with the increase in the number of eligible judgments and would effectually raise our characteristic threshold

On inspection of Von Wittich's figures it is seen that our results on the chromatic threshold correspond fairly well with his results on black ground at continuous view. The discrepancies which occur might easily be accounted for by any of the several influences already cited, or by their combined operation. Von Wittich does not clearly distinguish the chromatic from the characteristic colour threshold, so that we cannot compare our results on the latter with his.

The generally lower achromatic thresholds in our experiments than in either Von Wittich's or Aubert's may be explained largely by the greater accuracy with which we were able to measure the threshold sizes. Apparently Aubert and Von Wittich employed a method of measurement which provided for the recognition of a difference not less than one-fifth of a centimetre. This is seen especially in the results of Von Wittich, where the threshold angles calculated upon the basis of the registered distances make regular advances *per saltum* from 1′ 4″ to 1′ 14″, 1′ 23″, 2′ 17″, etc., in a way which would seem to indicate that the transitions in sizes had not been observed more minutely than as I have suggested. Our own apparatus was designed and constructed so that the transitions could be made in the most gradual way and the slightest changes registered with accuracy to the two-thousandth part of an inch, or even to the four-thousandth part, by estimating halves and quarters of the degrees on the disc. This was quite easy to do from the fact that each degree was about one-eighth of an inch in size.

Von Kries, in a chapter headed "Change of colour in small objects,"* touches upon one aspect of the problem of the space-threshold of colours. He is not dealing at length nor experimentally with it at all, but he gives a concise statement of some of the results which other men such as Von Wittich have reached in his historical account of this and allied problems. He lays particular stress upon the reciprocity which obtains between intensity and spatial size in the threshold perceptibility of colours. In other words, a coloured surface to be just seen as coloured must be larger spatially in proportion as the intensity decreases, and conversely the most minute size of coloured surface may be seen as coloured if the light is sufficiently intense. This mutuality of support between intensity and extension in regard to the first perceptibility of colour, besides being applicable to continuous surfaces, includes, he also observes, the case

* Gesichts Empfindung, p. 87.

of discrete points, as in the phenomenon which Fick described.* Not only will increased intensity secure the perceptibility of the colour of a smaller coloured surface but it will also increase that of a smaller number of discrete colour points, which according to Fick's observation co-operate with one another to produce a colour impression although they may severally be indistinguishable as coloured.

Von Kries has also noted that by decrease of the visual angles coloured surfaces pass through transitions of tone until finally at very small visual angles they lose all colour quality. He has traced the transitions for some colours. Red, he has noted, becomes colourless, but under circumstances that make it very difficult to observe, the limits of visibility usually coinciding with the loss of its colour quality. This is quite in conformity with our own experimental results. Orange, he says, appears red before becoming colourless. With us this took place generally in regard to orange on a black ground, although there were cases where particular observers saw orange as coloured just as long as it was visible at all. Yellow simply passes into white. Green no. 1 becomes white without the intermediate stage of yellow. Green no. 2 at the smallest visual angle appears greener (with some blue) and goes into white by way of yellow-green. Blue becomes colourless without change in tone. Violet becomes reddish at a small angle. These changes of course are for direct vision; for indirect vision the transitions are in some cases quite different.

Charpentier† has done some work which, though not bearing directly upon this problem, is suggestive. He has in the article referred to examined into the relationship of light intensity of coloured surface to the size of surface necessary for the perception of the surface as coloured. He sought to free his colours from the adulteration of ordinary pigments and to render them as nearly as possible spectrally pure. For example, he obtained his blue by the interposition of cobalt-coloured glass and glass coloured with oxide of copper. The first lets pass only the blue and the red rays, intercepting the green, while the second lets pass only the blue and the green, intercepting the red rays; the combined effect was to produce a blue resultant of tolerable purity, He had difficulty in producing a spectrally pure yellow (a difficulty which we also encountered in

* Pflüger's Archiv, Bd. vii, p. 152.

† "Sur la quantité de lumière nécessaire pour percevoir la couleur d' objets de différentes surfaces." Comptes Rendus, 1881, 1re Semestre, p. 92.

our work), and finally adopted as standard yellow a combination of all the rays which gave a predominant yellow element. This endeavour of Charpentier's to obtain pure colours was an advance in the treatment of this and kindred problems beyond the unscrutinizing haphazard adoption of pigments which had characterized some of the early work. The principle on which he worked is largely the same as we adopted, although a greater variety of absorbing media was employed in our experiments.

III.

METHOD AND APPARATUS.

The survey of the historical rise and development of the problem of the space threshold of colours is now completed. I will proceed to explain our own method of treating the subject experimentally. The apparatus which we used is somewhat complicated. It was designed by Dr. Kirschmann, to whom also especial thanks are due for supervision and suggestions throughout the course of the investigation.

In the first place it was thought desirable to conduct the experiments in a dark chamber with complete exclusion of daylight and to employ only artificial and therefore controllable illumination. Since our aim was to discover the effect of colour contrast upon the spatial threshold it became necessary to exclude, as far as possible, all such disturbing influences as would undoubtedly arise from the contrast of light intensities under conditions of ordinary daylight. Thus in using daylight we should have no means of controlling the absolute light intensity which illuminates the pigments employed, but by employing artificial light we should be able to equalize the apparent light intensity reflected from the coloured surfaces and so to rule out fairly completely the influence of intensity contrast. It is true indeed that in daylight the absolute light intensity shed at any time would be the same for both of the contrasting colours. But it does not follow that the apparent intensity, *i.e.* the light intensity given off from the pigment surfaces, would be equal. Nothing is more patent than the fact that almost any two pigments subjected to the same illumination, *e.g.* daylight, do not possess the same light-reflecting power, but that one will appear brighter than the other. We can make them of the same brightness by changing the illumination of the one while the other remains constant, and this can be done either by the interposition of some obscuring medium or by moving the source of light. The former method is not satisfactory because it usually introduces further complications in the nature of a change of colour, and hence impairs the value of the results. The other method of control, varying the distance of the source of illumination for one of the surfaces, is impracticable if we use daylight. Two sources of illumination are therefore necessary and one or both of these must be moveable to enable us to rule out all intensity contrast that is irrelevant to the problem and a disturbing influence. These conditions, we thought, could be best fulfilled by carrying on the whole investigation in a room from which daylight was wholly excluded, and where our sources of illumination were incandescent electric lamps of measurable illuminating power and arranged in a certain manner to be presently described. (See Fig. 1.)

The central part of the apparatus upon which the two sets of contrasting colours were set up consisted of a blackened table with two parallel vertical planes, also black, standing upon it at either end and about two feet apart. On the further plane was fastened a revolving disc, covered in sectors by the different pigment papers which were used as the foundation for producing, with various combinations, the several approximately pure spectral colours that we wished to examine. The nearer plane had an opening cut in it which was covered by a brass diaphragm (Fig. 2) with an adjustable square opening. The coloured light from the pigment papers on the further plane was admitted through the opening in varying quantities according to its size. The diaphragm consisted of two brass plates laid together, each having a square opening of two and a half inches diagonal, cut so that the diagonals were horizontal and vertical. The front plate was made to slide in metal grooves attached to the second plate, which was itself permanently fixed to the standing plane. A stationary screw, attached to the permanent plate and passing through a cylindrical nut on the sliding plate, furnished the means of moving the latter and of thereby controlling the size of the aperture from the zero point, where the two square openings just ceased to overlap, through the length of one diagonal, until they became completely coterminous at the maximum opening. The screw was manipulated by a crank handle and was so constructed that every complete turn moved the sliding plate just one-twentieth of an inch, or in other words increased the length of the diagonal of the square opening by one-twentieth of an inch. Each revolution of the screw, or one-twentieth of an inch increase in the diagonal, was indicated upon a graduated scale by a brass finger attached to the sliding plate. Furthermore, to the handle end of the screw was fastened a brass disc of about two inches in diameter, marked off at the circumference into fifty equal parts. As this disc revolved with the screw a peripheral movement through the length of one degree of its circumference would indicate that the sliding plate had moved one-fiftieth of one-twentieth, or the one-thousandth part of an inch. Starting from the zero point of opening we could thus produce in the diaphragm a square aperture, of which the diagonal measured one-thousandth of an inch. At any stage, besides the integral number of revolutions of the screw, which might be found from the index finger and its graduated scale on the groove, we could read the extra fractional part (in fiftieths of a revolution) from another indicator fixed above the revolving brass disc at a point corresponding to the zero point of its scale, that is, at the point where a whole revolution of the disc, and hence of the screw also, was just completed. We had in this simple arrangement a means of varying by gradual transitions the size without the form of the opening through which the coloured light under examination came, from zero up to a square opening of two and a half inches diagonal. Moreover the gradual increase or decrease was measurable with accuracy to the one-thousandth part of an inch, or to the two-thousandth or even the four-thousandth part, if we estimated halves and quarters of the degrees on the brass disc, which had considerable magnitude. In addition to this extreme accuracy of measurement it will be noticed that the apparatus afforded a simple and speedy method of ascertaining the diagonal size of the opening, for a mere glance at the two scales was all that was necessary to read the registration in terms of revolutions of the screw.

On the diaphragm were placed the ground or inducing colours on which we examined the colour threshold under contrast influence. In some experiments this diaphragm surface was transformed into a colourless ground, white, black or grey, by means which will be indicated further on. It may be mentioned that the two brass plates of the diaphragm were not laid exactly together, but that there was left a very thin interspace so as to permit of the insertion of pigment papers. The object of this was that the inner plate of the diaphragm might be given the same colour as the outer plate and thus a continuous coloured surface be presented throughout the movement.

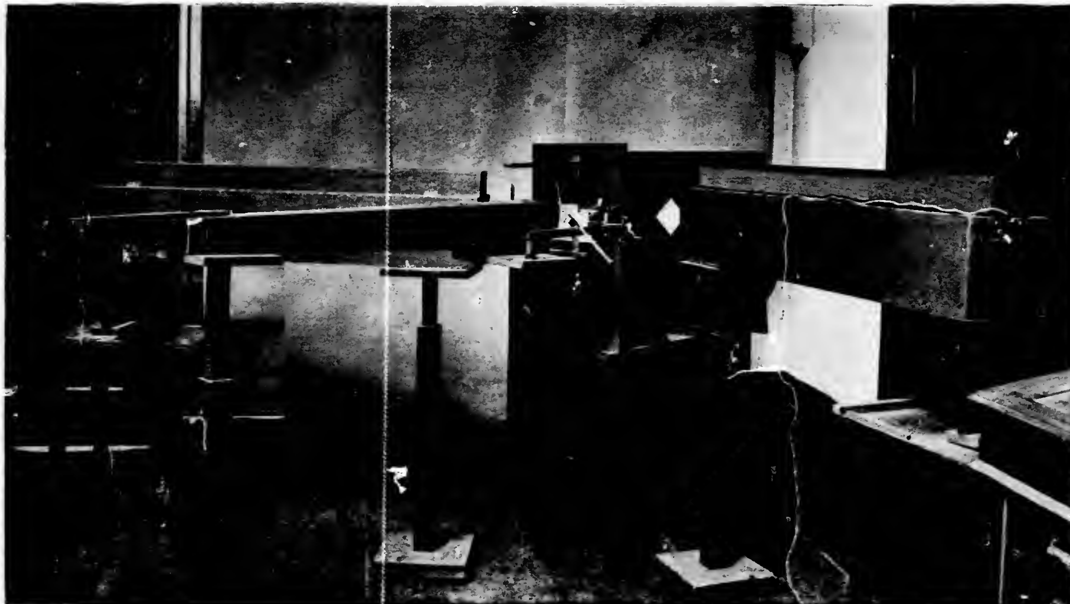

FIG. 1.

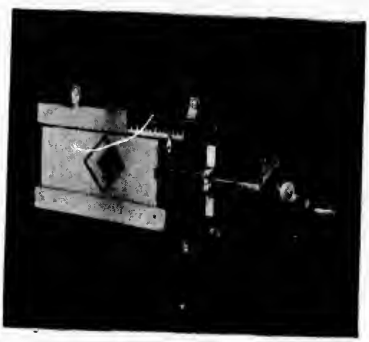

Fig. 2.

Here may be mentioned a nicety of construction which was of material importance to the reliability of the results. It became apparent that in putting the coloured paper on the diaphragm we must avoid exposing any ragged or white edges of paper at the margin of the square openings, lest the clearly defined edges of the cut on the outer plate should indicate too conspicuously the exact position of the aperture about to appear, and thus by leading to an anticipation of its appearance vitiate the results. To preclude this chance of error the pigment paper was first pasted on the brass plates, and then by two continuous cuts with a sharp knife, downwards only and slightly towards the brass edge all round each opening, the portion covering the holes came away leaving no uneven edges to the paper and no trace of white. Through the observing tube in front it was now impossible to distinguish lines where the surface of the upper plate ceased and that of the under plate seen through the square hole of the former began, but the whole appeared to be one continuous and uniform coloured surface. So complete was the disappearance of the lines, that very frequently, in fact generally, it was necessary to point out to the observer the neighbourhood on the coloured surface where the point of light would appear, lest he fall into the opposite error of not seeing the emergence of light when it was already visible, from his attention being directed to another portion of the field of vision. It happened, moreover, not seldom, that after being once seen the point of light would disappear again, in consequence of a slight deviation of the eye's fixation, and it would be only necessary to point out the neighbourhood again for the light to be seen. So much help to the observer was absolutely required to prevent his attention from wandering to all parts of the field of vision. But this could not endanger the results in the same way as the careless exposure of lines intersecting at the exact point where the spot of light was to be expected. It involves all the difference between giving the region in which the thing expected must be sought and locating the very point with mathematical exactness.

We had now our two contrasting surfaces, the inducing surface on the diaphragm structure, the induced seen through the opening of the diaphragm and variable in colour by revolution of the colour disc on the further plane. It has been indicated above that each of these surfaces was illuminated artificially and from separate sources. I will now explain the means by which this was done in such a manner as to rule out the disturbance of intensity contrast. The source of light in each case was an incandescent electric lamp of thirty-two candle power placed in a rectangular elongated box which was blackened inside and out, about five feet in length, with a square opening of eight inches to the side. The top was so constructed as to leave a slit along the full length of each box wide enough to contain the neck of a lamp in a wooden sliding frame. In this way the lamp could be moved through the entire length of the box. The open end of each box was directed towards the pigment surface, either the inducing or the induced, so as to permit the light from the lamp to fall obliquely upon it. The opening on top through which the lamp slid was covered by a lid hinged to the large box, for the purpose of preventing unnecessary escape of light. Since either or both the lights could be moved we had a very easy means of ruling out differences of light intensity in the two contrasting surfaces. All that was necessary was to alter the positions of the lights gradually until with a tolerably open diaphragm the light intensity of the two surfaces appeared equal. The point of equality was approached from both sides, first from above the equal point, where one surface was decidedly brightest, and then again from below, where the same surface appeared evidently less bright, so as to arrive as nearly as possible at the exact mean.

At this stage a difficulty presented itself, which it was of great importance to overcome, namely, how to get pure colours to operate upon. I have already pointed out that the work of Aubert and Von Wittich was gravely defective upon this score, and that ordinary pigments are by no means spectrally pure colours, but are the product in all cases of a mixture of spectral colour tones, and may even, as I have indicated, contain no rays of the kind after which they are named. Moreover, our incandescent lamp light is always somewhat yellowish and in being used to illuminate the pigments must cause a decided adulteration of colour tones even if the pigment colours were otherwise spectrally pure. Hence it was incumbent upon us to procure colours for investigation as free as possible from admixture with other colour tones. In order to meet this difficulty we decided to illuminate our pigment surfaces only by light transmitted through coloured media such as coloured glasses and gelatine films. Such media have the convenient property of absorbing some of the rays falling upon them and of allowing others to pass through. Of course different media will absorb and transmit differently and in varying degrees. Some will only weaken instead of totally absorbing the elements they interfere with and will consequently transmit the entire spectrum with weakened elements in some part.* In such a case an effective remedy is to increase the number of the interposed media until the disturbing elements are completely eliminated or at least eliminated to such a degree that the residue transmitted makes no material difference in the result. Moreover when a film or glass has the power of absorbing $\frac{1}{x}$ part of the blue rays, and it is placed before a coloured surface which reflects $\frac{1}{y}$ part of the blue rays which fall upon it, the joint effect will be that only $\frac{1}{x}$ of $\frac{1}{y}$ of the blue rays is reflected. If, for example, we have a blue pigment which reflects 10% of the red, 8% of the orange, 5% of the yellow, 10% of the yellow-green, 25% of the green, 98% of the blue and 40% of the violet rays, and we interpose before it a combination of blue gelatine and glass which transmits 6% of the red rays falling on it, 5% of the orange, 2% of the yellow, 6% of the yellow-green. 10% of the green, 100% of the blue and 20% of the violet, we get as a final colour result $\frac{3}{5}$% of the red rays, $\frac{2}{5}$% of the orange, $\frac{1}{10}$% of the yellow, $\frac{3}{5}$% of the yellow-green, $2\frac{1}{2}$% of the green, 98% of the blue and 8% of the violet, which indicates a very fair removal of the colour elements that obscured the spectral purity of the blue. In this way by various combinations of films and coloured glasses, using different combinations for the different colours desired, we were able closely to approximate to pure colour for the purposes of our experiments—a feature which was absent in the work of Aubert and Von Wittich. For each colour separately we found by actual trial the colour combinations, which under spectroscopic examination seemed to produce a colour most free from foreign elements. And although in no case did we get an absolutely pure colour, yet we succeeded so approximately that the colours which resulted may fairly be said to have been as good specimens of the various spectral colours as could be produced. At least it is safe to say that the errors which must have arisen from the use of pigment colours simply and without any correction were immensely reduced by this device and that our results are to that extent the more reliable. In the accompanying table (pp. 27 and 28) are shown the various combinations by which the colours employed for our

*Kirschmann, Ueber die Herstellung monochromatisches Lichtes.

experiments were produced according to the method indicated and also the synopsis of their spectroscopic analysis.

There remained a further consideration. The observer must be at some distance away from the coloured surfaces to be inspected, and that distance, as I have hinted in the beginning of the paper, must be constant; otherwise errors will creep in from the fact that the visual size of a surface depends not merely upon its absolute magnitude but upon its distance from the centre of the pupil of the eye as well. How then could we secure immunity from the danger of a disturbance caused by the dim light of the room being interposed between the observer's eye and the illuminated pigment surfaces? It is impossible to so darken a room that there will not remain some small reflected light capable of introducing a disturbance into the observations. It would be undesirable moreover to have the room absolutely dark, because in that case a fresh source of error would arise, from the fact that in total darkness the eye is incapable of holding its fixation for any length of time but moves unconsciously within a range of ninety degrees. This would be especially mischievous in experiments on the non-contrast light threshold of colours, where the front colour surface is not illuminated; since the observer might be looking completely in the wrong direction and not discover the emergence of the small point of light until long after the threshold mark. To overcome this difficulty we employed a long observing tube reaching from the observer to close proximity to the brass diaphragm. The tube was constructed of wood in the form of a truncated square pyramid; the larger end, with a diameter of about six inches, was in the vicinity of the brass diaphragm, while the observer's eye was at the smaller end, which was about two inches in diameter. It was blackened outside and the inner surface was lined throughout with black velvet, which, having a minimum power of regular light reflection, consequently reduced the disturbance of glimmer from the sides of the tube to the lowest possible point. Against the larger end of the tube was placed a black cardboard diaphragm, with a square aperture of about two and a quarter inches to the side, but cut diagonally or diamond-shaped like the opening in the brass diaphragm, the purpose of which was to delimit the size of the inducing colour. For obviously the latter could extend, at least so far as the observer was concerned, no further than to the boundaries of the opening in the observing tube. Over the cardboard diaphragm of the tube was arranged a

Table of Colours.

Position of Frauenhoffer's lines on the scale of the spectroscope.

B 421 (687 $\mu\mu$); C 425 (656.5 $\mu\mu$); D 437½ (589.5 $\mu\mu$); E 455½ (527 $\mu\mu$); b_4 459½ (517 $\mu\mu$); F 473 (486 $\mu\mu$); G 512 (431 $\mu\mu$); H (551) not visible. (393.5 $\mu\mu$)

Colour.	Pigment paper.	Illuminated by light from an incandescent lamp transmitted through			Visible part of the spectrum.	Remarks.
		White tissue paper.	Coloured glass.	Coloured gelatine films.		
1. Blue	Blue.			Blue.	450 to 500 (543.5 $\mu\mu$—445.5 $\mu\mu$)	
2. Violet	Blue.			Purple.	460 to violet end (515 $\mu\mu$ to violet end)	425 to 439 also seen dimly red. This with a very narrow slit is not noticeable.
3. Purple	Purple.			Purple.	450 to red end (543.5 $\mu\mu$ to red end)	Red between 420—430. (694.6 $\mu\mu$ to 626.5 $\mu\mu$.)
4. Orange	Orange		2 orange-yellow	Yellow	432 to 448 (616.5 $\mu\mu$ to 550 $\mu\mu$)	
5. Yellow I	Yellow	1 sheet	1 orange-yellow	Yellow	430 to 456 (626.5 $\mu\mu$ to 525.5 $\mu\mu$)	
6. Yellow II	Yellow		1 orange-yellow	1 yellow and 1 green.	438 to 460 (584.5 $\mu\mu$ to 515.3 $\mu\mu$)	
7. Yellow-green	Yellow		1 yellow-green	Green	446 to 462 (557 $\mu\mu$ to 510.5 $\mu\mu$)	The spectrum ends are very abrupt.

TABLE OF COLOURS.—*Continued.*

Colour.	Pigment paper.	Illuminated by light from an incandescent lamp transmitted through			Visible part of the spectrum.	Remarks.
		White tissue paper.	Coloured glass.	Coloured gelatine films.		
8. Green	Green		1 blue-green	Green	445 to 470 (560.5 $\mu\mu$ to 492 $\mu\mu$)	
9. Blue-Green	Blue-green		1 blue-green	Green	448 to 478 (550 $\mu\mu$ to 477.5 $\mu\mu$)	
10. Red	Red		1 red		423 to 435 (671.5 $\mu\mu$ to 600.5 $\mu\mu$)	
11. Grey I (yellowish).	Grey				425 to —— (656.5 $\mu\mu$ to ——)	Full spectrum, greatest intensity at yellow.
12. Grey II (greenish).	Grey			Blue	440 to —— (479.3 $\mu\mu$ to ——)	Maximum intensity at green.

shutter, which could be used to shut off all the light from the illuminated pigments and thus to give the observer's eye a chance to rest between observations. In our experiments it was of course necessary to take the further precaution, after opening the shutter, of pausing briefly to allow the eye to accustom itself again to the bright light and colour. Not to use this precaution would be to introduce the disturbance of successive brightness contrast, just as to neglect to close the shutter frequently would admit the vitiating influence of retinal fatigue.

The small end of the observation tube was kept stationary at the chosen distance from the brass diaphragm. But because of the fact that the opening in the brass diaphragm could be enlarged only on one side, it became necessary to make the larger end of the observing tube also moveable, in order to keep the brass diaphragm opening always in the centre of the field of vision as delimited by the diaphragm of the observation tube. It would not do, however, simply to make the end of the tube move at the same speed as the sliding diaphragm plate, for this would be too fast for the purpose, which was to keep the induced surface marked out by the brass diaphragm opening always in the centre of the field of the inducing or ground surface. For it is evident that the centre of the increasing square aperture in the changing diaphragm moves exactly half as fast as the moving plate which effects its increase. This we can see if we consider that at the zero point the centre coincides with the moving angular point of the plate, but that when the latter has moved any distance the centre is exactly half-way between the zero or starting-point of the moveable plate and its latest position. In order to secure a movement of the observation tube of exactly the desired speed we introduced into the apparatus a very simple leverage device which accomplished the result automatically. We employed an arm twice as long as the distance of the diaphragm plate from the observation tube; one end was fastened to the sliding plate of the brass diaphragm, while the other was pivoted to the table upon which the observation tube stood. From the middle of this arm an attachment by pivot was made with the end of the observation tube. Then as the plate was moved by the operator the arm turned round the pivot on the table, drawing from its middle point the end of the observation tube. This contrivance completely served the purpose of securing an automatic steady shifting of the tube, so that the colour transmitted through the opening in the brass diaphragm was kept precisely in the centre of the inducing ground as delimited by the diaphragm of the observation tube. We were thus enabled to escape from the irregularities of our preliminary method, which was independent manipulation by the operator. The arrangement worked in all respects satisfactorily. So little did the extra weight of the tube obstruct the rotation of the screw which moved the diaphragm plate, that the difference in the ease of the movement was scarcely perceptible to the operator.

There are a few other considerations which I must briefly dwell upon in order to give a full explanation of our experimental equipment. We made some experiments with a black ground, the results of which have been already given in this paper, by way of comparison with those of Von Wittich and Aubert. Although superior to the work of these experimenters both in accuracy of measurement, as can be seen from the description of our apparatus, and by reason of the employment of a black ground that is practically constant, they were not free from errors due to the other causes which I have alluded to in discussing the results of Von Wittich and Aubert. All the disturbances arising from the unequal light intensities of the pigments, when illuminated by daylight whose intensity is uncontrolled and uncontrollable, remained. In order to get a fair approximation to the threshold perceptibility of colours on a black ground it would be necessary not only to use a true black (discarding black paper which reflects considerable light) but also to eliminate any inequality among the different colours of brightness contrast with the black ground. Without this precaution we could not be sure how much more for one than for another colour our judgment was affected by intensity contrast. But if we remove this inequality by making all the colours equally bright, then, although we cannot claim to have eliminated intensity contrast from our conclusions, we can safely claim that we have made it a constant quantity for all the colours. It will enter to exactly the same degree for each colour, since the ground is constant and the brightness of the colours the same. To secure the total removal of intensity contrast it would be necessary, not only for the relation of the brightness of the colours to the ground to be constant, but that that relation should be equality. The ground should have the same brightness as the several colours. This could be effected in the case of a colourless ground only by making it grey and with a system of controllable illumination such as will be described presently. First, however, I will explain the method in which we conducted our experiments with an absolute black ground and sought to reduce the errors of uncorrected pigments and their uncontrolled brightness intensities to a minimum, while converting the unavoidable intensity contrast into a constant and evenly distributed influence for all the colours.

In explaining our mechanism for regulating the contrast in the case of a black ground, as employed in its final form, I shall have occasion at the same time to refer to the method by which we sought and practically secured an immunity from brightness contrast in our experiments with a coloured ground In fact the latter is the key to the former and the explanation of one will suffice for both.

It has already been said that we discarded daylight illumination for the reasons advanced. The colours which we employed for experiments with a black ground were twelve in number. Their composition I have sufficiently described in the schedule of colours (p. 27) giving their spectroscopic analysis. They were the same colours at the same brightness intensities which we also employed in our experiments with coloured grounds, and were exceptionally successful approximations to pure colours. I will now show how with these colours and under artificial illumination we secured, first the absence of intensity contrast for all the colours on coloured grounds, and secondly from this vantage ground a basis for the limitation of intensity contrast in the case of a black ground to a constant quantity for all the colours.

The diaphragm surface being illuminated by the left-hand lamp at a certain position in its box, the diaphragm was opened to about half its extent, and the other lamp which illuminated the colour on the colour disc (*e.g.* blue) was adjusted to such a position that the observer at the tube judged the light intensity of the blue to be exactly the same as the light intensity of the diaphragm surface. This judgment was, of course, not given instantly nor at random, but was reached gradually, both from below, where the blue seemed the darker, and from above where it seemed the brighter. The position of the shifted lamp when the two coloured surfaces were judged equal in brightness was marked. The similar positions of the lamp for green, red, yellow, etc., throughout the entire set of colours were also marked, and thenceforth always used in the composition of the several colours respectively. Thus, by this simple means, the light intensities of the colours for examination were all equalized with fair exactness. In other words by this practicable method we eliminated for experiments with coloured grounds the influence of brightness contrast.

It is obvious that the success of the above device is dependent upon the reliability of the observer's estimation of equality, but the chances of error were minimized by testing the judgments of one person by those of others. Peculiar difficulty, moreover, in judging equality of light intensities occurs where the surfaces examined are coloured. It then is necessary to abstract attention from the colour altogether, and give it solely to the brightness of the light, a very difficult achievement at first. However, it was proved that the difficulty is overcome by a little practice, and we found in fact that the independent estimates of practised observers were in very close correspondence.

All that was necessary now to render constant the brightness contrast between the various colours and a black ground was simply to convert the coloured ground into absolute black without disturbing the intensities of the induced colours. This was expeditiously and thoroughly done by enclosing and shielding from reflected light by means of black velvet the interspace between the end of the observation tube and the brass diaphragm which was to be converted in black. This served practically the same purpose as the annex to the tube described in connection with our daylight experiments earlier in this paper. It was not found necessary to employ the annex because of the fact that the experiment room was now dark, and it required very little further obscuring in addition to the removal of the lamplight to produce a complete black surface on the diaphragm. In this manner, with such an absolute blackness of surface and with colours all of uniform brightness intensity as well as severally purified from the adulteration of foreign colour tones, it became possible to remove from our observations the multitude of obscure immeasurable influences such as vitiated the results of previous investigations.

In the formation of a grey ground we made a departure from the method of our other experiments. We of course retained the lamp illumination of the colours in order that they should be the same as those experimented with on the other grounds. But we encountered a difficulty in securing a good grey ground by the same method of lamp illumination as we used for the coloured grounds, owing to the fact that the light from the incandescent lamp had a decidedly yellowish tinge and shining upon the best grey pigments produced a yellowish grey ground. It was found next to impossible to obtain absorbing media which would remove this tinge of colour without introducing some other colour element in its place. The nearest approach that we could make to a grey by the use of absorbing media was our grey no. 2, described in the table giving spectroscopic analysis of the colours, and this was somewhat bluish just as the grey no. 1 was somewhat yellowish. In order, therefore, to avoid this difficulty and obtain as pure a grey as possible, we decided to use for the grey ground a daylight illumination of a grey paper surface covering the diaphragm. To secure this without interfering with the lamp illumination of the colours on the further plane, we constructed a shaft, eight inches square and nine feet in length, interior measure, which we used to conduct the daylight from outside to the vertical surface of the brass diaphragm. It was made to bridge the distance from the only window of the room, about seven feet from the floor, to the stand, which was on a level with the lower part of the brass diaphragm, or about two feet and a half from the floor. One end was inserted into a square aperture in the shutter which darkened the window, fitting as closely as possible without interfering with ease of insertion. In order to support the shaft and also to render it more easily manageable from the floor there was a platform attachment to the aperture in the window-shutter, made in box form like the shaft itself, but without a top, and large enough to enclose the end of the shaft. This support was obliquely placed upon the shutter and pointed downwards as the shaft itself did towards the apparatus beneath. The light which would have found its way through the small unavoidable crevices in such a structure was effectually shut out by means of a black cloth screen over the place of junction. The shaft was blackened outside, and inside was painted white throughout. The light was reflected into the shaft by a large mirror outside the window, and the intensity of the light so thrown upon the grey paper was controlled by means of a second reflector, placed below the lower end of the shaft in such a way that the light coming diagonally and from above upon the grey surface could be deflected and thrown perpendicularly upon it. This arrangement was of use on dark days to bring the brightness intensity of the grey up to the same standard of brightness as obtained uniformly among the artificially lighted colours to be examined upon this ground. On brighter days the mirror could be changed so as to vary the obliquity in the incidence of the light, and thereby the daylight illumination of the grey could be controlled and approximated to the standard brightness of the colours. On very bright days it was found that the second mirror was not necessary at all, since the light as it came from the shaft was sufficient to produce the required intensity of the grey.

By this expedient of controlled daylight illumination for the ground we were able to secure a fairly good grey, though it sometimes had a bluish tinge. The method was only tentative, but it was found to serve the purpose better than any other discoverable at the time. One grave disadvantage under which it laboured was due to the fact that daylight illumination is somewhat unsteady, being subject to the overshadowing of passing clouds. We sought to eliminate this influence so far as possible by conducting the experiments with the grey ground on cloudless days or when the sky was uniformly cloudy. If again the operator noticed a sudden change in the brightness of the grey he paused in the experiment, closing the shutter of the observation tube until the ground regained its previous intensity.

In concluding the description of our apparatus it must be mentioned that the observer was behind a large black cardboard screen through which the observation tube passed. The screen extended on either side of the tube for at least three feet as well as above and below it, so that the observer was completely precluded from receiving any hint as to the nature of the colour combination introduced from the sight of coloured light reflected from the walls. The only way of seeing the coloured light was through the observation tube itself, after the intervening shutter had been removed.

It may be well before passing on to a discussion of our experimental results to give some explanation of the tables and charts. The former speak for themselves. They are simply the classified record of our averaged results on the three discriminated space thresholds. In the first main section (I) are given the results for the achromatic threshold, in section II those for the chromatic threshold, and in section III those for the characteristic threshold. Under each section we have specified always in thousandths of an inch the diagonal measurements of the diaphragm opening. On this basis we calculate the threshold size in the form of visual angles according to the following simple method:

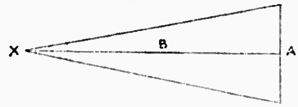

FIG. 3.

In the accompanying figure (Fig. 3) let A represent the length of the diagonal of the diaphragm aperture at any point which forms the threshold, the distance B being fixed for all sized apertures (172 centim.) as the permanent distance of the observer from the diaphragm. The angle x which the diaphragm diagonal subtends at the observer's eye may be calculated by the following formula:

$$\text{Tan} \tfrac{1}{2} x = \frac{\frac{A}{2}}{B}$$

$$\therefore \text{Log tan} \tfrac{1}{2} x = \log \frac{A}{2} - \log B.$$

The results of such calculations have been placed in the third sub-column under each main section where there are three sub-columns, or in the second where there are only two. In some cases we have also calculated the visual angles on the basis of the diameter measurement of the diaphragm aperture. These are given in the second sub-column of the three, and were obtained from the diagonal calculations by using the relation of the diameter of a square to the diagonal, which is $1 : \sqrt{2}$. Hence, the visual angle subtended by the diameter being represented by y, while x stands for the diagonal visual angle, we have:

$$\text{Tan} \tfrac{1}{2} y = \frac{\tan \frac{1}{2} x}{\sqrt{2}}$$

$$\therefore \text{Log tan} \tfrac{1}{2} y = \log \tan \tfrac{1}{2} x - \log \sqrt{2}$$

$$= \log \tan \tfrac{1}{2} x - \tfrac{1}{2} \log 2.$$

IV.

RESULTS AND THEIR INTERPRETATION.

Achromatic Thresholds.

(1) Black Ground.—By reference to the accompanying tables, the general relationships which obtain among the achromatic thresholds on a black ground will be manifest. Tables I, II and IV contain, under section I, the results of the achromatic thresholds for three observers respectively, Dr. Kirschmann, Mr. Preston and

Mr. McCallum. The tables representing the observations of Dr. Kirschmann and Mr. Preston were based upon the results obtained from several sets of observations, as many as six in the case of Mr. Preston and three in that of Dr. Kirschmann, whereas Mr. McCallum's table represents only one series of observations. It is obvious, therefore, that where there are any serious discrepancies between Mr. McCallum's observations and the joint testimony of the other two, the presumption is that their sensibility is more accurately represented than is that of Mr. McCallum.

It will be noticed by reference to Tables I, II, III and IV that the colours which, when viewed on a black ground, have lowest achromatic space thresholds are blue and blue-green. The maximum point is attained by the red, while the colours intermediate between red and blue show a somewhat gradual transition from the highest threshold point to the lowest. The most abrupt break is at the yellow-green, where a sudden deviation upward occurs, more marked in the case of Dr. Kirschmann than in that of Mr. Preston. There is not complete agreement between the observations of Dr. Kirschmann and Mr. Preston in regard to violet, which for Dr. Kirschmann (in our marking) has an achromatic threshold considerably higher than purple, but lower than purple for Mr. Preston and also for Mr. McCallum. It will be noticed also that the achromatic threshold of grey no. 1 is lower than that of grey no. 2 for all observers. A peculiarity of red, as distinguished from the other colours when viewed on a black ground, is that it is always and by all observers seen from the very first as coloured. In other words, whereas the other colours can for the most part and with the majority of observers be seen as colourless points of light or simply as something different from the ground, at sufficiently small visual angles, red is conspicuous as having, at least on a black ground, no strictly achromatic threshold. We have, however, used the term achromatic threshold to embrace the visual angle at which a colour is first seen at all, and hence it may be applied to red as well as to the other colours which are first seen as colourless light. It will be found that all the observations recorded agree in this peculiar behaviour of red on the black ground. Some of the other colours are occasionally seen also coloured from the first, but these instances are probably due to accidental circumstances, since even the same observer will at other times see them colourless. In the case of orange, Mr. Preston sees it always coloured, but Dr. Kirschmann and

Mr. McCallum both see it first as colourless light in the majority of their observations, though in some cases, like Mr. Preston, they see it coloured from the first.

It is a noteworthy fact that the region of highest achromatic space thresholds is the red end of the spectrum, and the region of lowest thresholds is that which embraces the other end of the ordinary spectrum, from blue-green to violet, with purple as a mean between the two. This position of purple coincides very appropriately with its known spectral relationship to red and violet, as a transition between these two ends of the ordinary spectrum. This is shown in the " inverted spectrum,"* where purple, which does not appear at all in the ordinary spectrum, is seen as the middle colour, while red and violet are its immediate neighbours on either side.

It might at first seem rather peculiar that the lowest achromatic thresholds should be found in the blue, blue-green and violet region, as these colours are usually regarded by us as less bright than such colours as orange and red, which, according to our experiments, have a much higher achromatic mark. But we must not forget that the colours were reduced so far as possible to the same brightness, so that their comparative positions as regards threshold visibility do not rest upon a basis of brightness, but are due to some other cause inherent in the quality of the coloured light and in the nature of the sensibility to which it appeals. A graphic representation of the relations of the achromatic threshold on black ground is given in Curve I of Figs. 4, 5 and 6, the latter representing the results of an average of observers.

(2) Grey Ground.—If we consider the achromatic threshold results on a grey ground we notice in the first place that the thresholds are, as a whole, considerably higher than those obtained on a black ground. This was to have been expected from the great brightness contrast which was in play in the experiments with a black ground. The sole object, indeed, of performing the experiments on the grey ground was to secure as far as possible an immunity from this contrast in brightness between the colour and the ground. Hence, if our measures were at all effective in achieving the end for which they were devised, we should look for an increase in the threshold sizes.

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*Colour Saturation and Its Quantitative Relations, by A. Kirschmann. (American Journal of Psychology, Vol. vii., No. 3, page 389.)

Examining Tables V, VI and VII (Sec. I) we notice that the relationships of the achromatic thresholds among the colours are considerably altered from those which we found to obtain on the black ground. Instead of red being the region of highest achromatic space thresholds and blue that of the lowest, with the intermediate spectral colours forming a graduated series between, we find now a tendency to decrease among the red thresholds and to increase among the blue. In fact, so great is the change that red has the lowest threshold of all the colours on the grey ground, though not much lower than some colours of the blue-violet region. We notice, however, that in the region from orange-yellow to green, inclusive, the same mutual relations of the parts hold good as on the black ground.

The only serious alterations occur in the thresholds of the colours at the ends of the spectrum. What can be the explanation of this discrepancy between the results on a grey and those on a black ground? I have already pointed out that in both cases the colours were of equal intensity as light, so that their brightness in relation to the ground should in both cases be uniform for all the colours. It cannot, therefore, be attributed to any change in relative brightness. The only difference in the two sets of circumstances was that by substituting a grey for a black ground we removed the inequality of brightness intensities between ground and colour, while retaining the uniform intensity of the latter. But all that we should expect from such a change would be a general elevation of the achromatic thresholds, without disturbance of their mutual relations. We know that the change to the grey ground from the black would modify the brightness intensity of the colours relatively to a percipient, though not absolutely. For if the existence of contrast of brightness means anything it means that the surface observed by the percipient appears to possess a greater intensity than it otherwise would have. Consequently to do away with light contrast would be equivalent to lowering the light intensity of the colours all round—so far at least as the achromatic space thresholds are concerned. But it does not appear that these considerations offer satisfactory explanation of the actual facts observed. It is conceivable that such a change might introduce some modifications into the system of achromatic threshold relations, since equal increases or decreases in the light intensities of colours are accompanied by unequal degrees of change in saturation, and the presumption is that the achromatic space threshold of a colour is quite as much a function of the saturation as of either of the other variables of light phenomena, viz., brightness and colour tone. This supposition, however, even if admitted, does not account for the fact that when a grey instead of a black ground is employed the red region of the spectrum (including orange) is converted from the region of highest to that of lowest achromatic thresholds, while the thresholds of the blue-violet region are raised.

Possibly the explanation of this phenomenon depends largely upon the fact that in spite of our care we were unable to exclude completely the colour element from our grey ground, while keeping it at an intensity equal to that of the colours under examination. The grey which we used was, as has been said, slightly bluish, more conspicuously after exposure to the yellow light of the incandescent lamps, and this bluish tinge in the ground may account for the increase in the blue-violet thresholds and the comparative lowering of those of red and orange. The assumption is here involved that the achromatic space threshold of colours is dependent to some degree upon the contrast relations of colour qualities. Why blue should tend to influence red more than orange is a matter upon which light will be thrown by the exposition of the contrast relations of the actual characteristic and chromatic space thresholds. In the meantime it is sufficient to anticipate the results there reached, and say that we have found blue and red to influence each other's space thresholds more than blue and orange or red and green, the ordinary complementaries. Accordingly, my suggestion is that since the achromatic space threshold may be considered as simply the zero point of perceptible saturation, the same modes of behaviour may obtain here as in the higher degrees of visible saturation. This is not offered as an *a priori* deduction from the relationships of colour contrast, but merely as a plausible theory in explanation of the phenomenon observed; its validity will be strengthened if it is confirmed in the case of achromatic space thresholds on coloured grounds.

Before leaving the observations with a grey ground I wish to mention a fact that is noted in our results. Red, which uniformly appeared coloured when first visible on a black ground, has usually on a grey ground a distinct achromatic threshold. The achromatic threshold is represented for some observers by the curve I in Figs. 7 and 8.

(3) Red Ground.—On reference to Tables VIII, IX, and X (Sec. I), which embody the results of our observations of achromatic

thresholds on a red ground, it will be noticed that the highest thresholds are at the red end of the spectrum, being those of orange, orange-yellow, and purple, while the lowest are in the regions of green and, more especially, blue. The threshold of purple was unusually high, for purple on a red ground is not always seen as a point of light but requires to become of considerable size before it can be distinguished from the red of the ground. Some of our observers, however, did see the purple as a spot of colourless light, and consequently their curves show a lower achromatic threshold of purple than that of Dr. Kirschmann for either eye. The greys occupy a middle place on this ground, and grey no. 1 has a tendency to be somewhat higher than grey no. 2, a significant fact when we remember that grey no. 2 was slightly bluish in tone.

It will be seen that the supposition by which we sought to explain the disturbance of achromatic space threshold relationships among the colours in changing from the black to the grey ground is, according to our anticipation, verified by the results with a red ground. We find that on a red ground the blue and the green have the lowest thresholds, the blue even lower than the green.

(4) Blue Ground.—The results with a blue ground (Sec. I of Tables XVI, XVII, XVIII, XIX, and XX,) are similar to the foregoing. The regions of lowest achromatic space threshold are those of red and orange-yellow. The threshold of orange itself is uniformly somewhat higher than that of either red or orange-yellow. The regions of highest threshold are those of the colours nearest to blue on both sides of the spectrum, viz., green, blue-green, violet, purple, and yellow-green. The greys are closely related, as we might expect, grey no. 1 having a lower threshold than grey no. 2. The principal fact to be noticed in these results is the lowness of the threshold of red which in two out of five of the tables is the lowest point and in the other three is but slightly above that of orange-yellow, the actual lowest for those observers. This would indicate the same tendency already observed in the case of the grey and the red grounds, which is that red and blue are in close correspondence in reference to the facility with which each can be seen achromatically on a ground of the other. It is also rather a peculiar circumstance that orange itself is not influenced to the same degree by blue as either red or yellow no. 1 (orange-yellow) in the direction of low achromatic space threshold. It is natural to suppose that if the achromatic perceptibility of colours is dependent upon the colour of

the ground it will be determined by the ordinary complementary colour relationships. But actual observation does not bear out this supposition, and thus shows us how precarious is all such *a priori* inference from the relations of one limited realm of colour phenomena to those of another yet to be explored. It also shows the necessity and utility of some such provisional hypothesis subject to the evidence of facts. For unless we had anticipated by some vague expectations the way in which the colours would behave under new conditions we should never have appreciated the significance of their non-conformity to colour laws already known.

(5) Green Ground.—On the green ground (Sec. I of Tables XI, XII, XIII, XIV, and XV) the lowest achromatic space thresholds were in the region of the red, except in the case of Dr. Kirschmann, whose observations were not numerous enough to afford a basis for satisfactory comparison with the others. Taking the uniform testimony of the other observers we find that while red has the lowest threshold, the colours of highest achromatic space threshold are uniformly those on either side of green in the spectrum, viz., blue-green, yellow-green, blue and violet. Purple stands in about a medium position. The unanimity with regard to the relative positions of blue and violet is not quite complete. Two observers (Dodds and Creighton) made the threshold for blue lower than that for violet, while all the others gave it as higher. The greys occupy for the most part a middle position, grey no. 1 being below grey No. 2, as was the case when seen on the blue ground. The same state of affairs is thus found to obtain among the achromatic thresholds on the green ground as was noticed on the other coloured grounds. The complementary colour has not the lowest achromatic threshold.

Before concluding the discussion of the achromatic space thresholds I wish to call attention to a significant side light which our experiments in this sphere have thrown upon the ordinary component theories of colour. The Young-Helmholtz theory, for example, is that the three colours, red, green and blue (or violet), are the components both of white light and of all other colours. Each of these original colour sensations is supposed to have a physical basis in the nervous organism, either in the form of special kinds of nerve-fibres which when excited react so as to give rise to their respective colours, or by way of a special kind of visual substance. According to this theory we should expect that one of the composite colours, such as yellow or purple, would at smallest visual angles have a tendency to disappear into one or other of its components, on account of the isolation of the nervous elements stimulated by so small an exposure of coloured surface. But the contrary is the case as we have seen. Instead of vanishing into some other simpler colour element the alleged composite becomes a colourless point of light, a phenomenon which this component theory fails to explain. Again, although it is favourable to such a theory that red does not lose its colour quality on black ground at very small visual angles without becoming forthwith invisible, yet the fact that green and blue (or violet), the other so-called original component colours, dc lose their colour quality and become colourless light under the same conditions is entirely inconsistent with it. For if these colour tones are the constituents of white light, we should never expect to find, as is the case, that they lose their colour at small angular sizes and appear as that white light which is supposed to be the product of all three. The same criticism may be urged against Maxwell's theory, which selects for the component colours vermilion, ultramarine and emerald-green.

The achromatic space threshold of the colours on coloured grounds is represented in Figs. 9, 10, and 11 by the dotted curves.

Chromatic Thresholds.

(1) Black Ground.—In our chromatic space thresholds on a black ground as shown in Section II of the corresponding tables, it will be seen that the agreement among the different observers is not by any means complete, although with one exception (Mr. Preston) they are not seriously at variance Apart from Mr. Preston's testimony the results are substantially alike, from purple up to yellow-green inclusive. In the case of green there is considerable disagreement, but after passing green the results again agree fairly well up to blue. Mr. Preston's observations, however, contradict those of the others almost at every point from the red to the yellow-green, inclusive. With so little unanimity among the other observers as to the chromatic space thresholds on black ground we can scarcely find sufficient data for a secure judgment. It is, therefore, difficult to speculate as to the cause of Mr. Preston's noticeable disagreement with his fellow-observers. But we may remark that the strongly emphasized discrepancy in the matter of orange is very probably due to an unusually keen sensibility for orange on the part of Mr. Preston

His six observations on the chromatic threshold of orange were exceptionally close to each other in threshold magnitude and were severally identical with what we named the "achromatic threshold" for orange. In other words Mr. Preston not only saw orange at a very small visual angle but he saw it always coloured as well. Another peculiarity in Mr. Preston's chromatic space thresholds on black ground is that for him, so far as recorded, the colours which have the lowest chromatic space thresholds are the blue-green and violet. no observations having been made by him with blue on this ground.

The other observers are quite unanimous in making red the region of lowest chromatic space thresholds, with a tendency to give a correspondingly high position to blue. They all seem to agree, moreover, in first seeing yellow no. 2 as coloured at , high spatial threshold. Grey no 2 on this ground, including Mr. Preston's observations, uniformly shows a higher chromatic space threshold than grey no. 1, which is not inconsistent with the threshold position of blue itself since the grey no. 2 was bluish.

One noticeable fact about these chromatic space thresholds on a black ground is that the colours between purple and yellow according to the arrangement of the spectrum are nearly always seen reddish first, while the colours between yellow-green and blue are nearly always seen first as blue.

It should be pointed out that the curves representing the chromatic threshold in our representations are always formed by alternate strokes and dots and are numbered II.

(2) Grey Ground.—Here we notice that the colour which has decidedly the lowest threshold is red in the case of two out of three observers, while for the third it is yellow no. 2. The other comparatively low thresholds are those of orange and perhaps green. The higher markings are for purple, yellow no. 1, and perhaps blue-green, blue and violet. In the cases of blue and violet there is not complete unanimity among the observers, the chromatic space threshold of violet being low for Mr. Creighton as compared with that of blue, and for the writer (Mr. Lane) that of blue being low in comparison with the rest. Mr. Creighton's chromatic thresholds for blue are considerably higher throughout than those obtained by the other two observers. In the violet the reddish elements appeal to him most strongly and at smallest visual angles, as is shown by the fact that the violet always

was seen coloured by him first as red. This, however, is not conclusive, for violet first appears to the other observers also not as bluish but generally as reddish (sometimes with an orange, sometimes with a purple tinge). Nevertheless it is evidence of some individual peculiarities of sensibility. The results of Mr. Creighton's observations, which were averaged to obtain the final representation of the chromatic space thresholds of blue on grey ground for him, were too much in agreement among themselves to suppose that the comparative highness was due to some accidental conditions external to the percipient. I am aware that in our experiments on a grey ground our work was liable to be disturbed by sudden changes in the illumination of the ground which were due to passing clouds. Since, however, the results which were averaged were obtained on separate days, it is unlikely that uniform conditions of disturbance were accidentally present in all instances. There is no doubt, moreover, that the presence of a slightly bluish element in our grey ground would have the effect of raising the chromatic threshold of blue, except where, as in the case of the writer, it was counterbalanced by extra sensibility to blue.

(3) Blue Ground.—In the results on a blue ground we notice the peculiar fact that the regions of lowest space threshold are red and yellow no. 1, the former being in all cases except one (mixed observers) lower than the latter. We notice further that orange has its chromatic space threshold considerably higher than red and for the most part higher than yellow no. 1. After yellow no. 1, following the arrangement in the spectrum, the colours form an ascending series up to blue-green where the thresholds reach their maximum. In the case of green, however, the gradual ascent is broken, green being in one case lower than yellow-green (Dr. Kirschmann's left eye) and in one case higher than blue-green (Mr. Robinson). The former deviation is probably due to the fact that only one set of observations was made by Dr. Kirschmann with his left eye, and that as an offset to his observations with the right eye. The chances are that more observations would have corrected the want of conformity in this instance. The other deviation is not so easily explained. The observations that Mr. Robinson made for this colour were six in number and they all gave a high chromatic space threshold. It can scarcely therefore be accidental, and as the external conditions were the same for all the observers we must ascribe it to a peculiarity in

Mr. Robinson's sensibility. We must not however conclude that he cannot see green at a lower visual angle than that indicated by this threshold, for he sees blue-green *as green* at a very much lower angle. Mr. Dodds also differs from the other observers at yellow no. 1; his threshold for that colour, though not absolutely higher, is yet relatively to orange higher than obtains with them. His observations were quite consistent among themselves and there seems no other reason for the divergence of his results than an individual difference of sensibility. Violet has a higher threshold than purple as a rule, perhaps because of its close qualitative affinity to the blue of the ground. Grey no. 2 is also uniformly much higher than grey no. 1 on this ground, as was to have been expected from its bluish tinge.

The most noteworthy feature, however, about these results on a blue ground is the fact of the lowest threshold being in the red instead of in the orange where we should naturally look for it. The action of colours by contrast in inducing their complementaries upon contiguous or neighbouring surfaces would lead us to expect that in these experiments the emerging surface would tend to appear in the colour complementary to that of the ground. In other words we should expect of a blue ground that it would tend to make every colour at first appear orange or tinged with orange. But as a matter of fact nearly all the colours on a blue ground are seen first as red, even the greens appearing as reddish or brownish (which is a weakly saturated red or orange). It might be said that the facts so far conform broadly to the expectation, because the red or reddish, which is the first chromatic appearance of the colours on blue ground, at such small sizes is practically the same as a faint orange. But we should also expect that orange itself would have a lower chromatic space threshold than red or yellow because of the accentuation of the orange element through contrast. Yet such is not the case. Here as in the achromatic sphere the blue ground seems rather to facilitate the chromatic perceptibility of colours which are not fully complementary to the contrasting ground.

(4) Red Ground.—Turning to our results for chromatic space thresholds on a red ground we notice by reference to the tables that the region of the highest threshold is purple, while the lowest is in blue and the immediately adjacent spectral colours. According to the ordinary complementary relationship of red and blue-green the lowest chromatic space threshold should be that of blue-green. But

although it is low in comparison with purple yet it is unvaryingly higher than blue. With this should be taken into account a fact similar to what was noticed on the blue ground, that the colours are first chromatically seen in nearly all cases as blue instead of the expected green. In Dr. Kirschmann's observations with either eye every colour except purple is seen coloured first as blue, purple being first seen as red. In the set of observations by various observers blue is not so uniformly the vesture of all the colours at their chromatic space threshold, but it prevails. The only colours which are not generally first seen as blue are orange, purple and yellow-green. Orange appears sometimes green, sometimes as a "dirty" yellow. Purple becomes visible as red, yellow-green is seen usually as a dark blue-green, sometimes as green, and three times out of ten even as bluish. It is noteworthy that blue-green and green are seen not as green mainly, when first seen coloured, but as blue. It thus appears that blue-green, the complementary of the red ground, instead of being induced as the first form in which other colours appear coloured on red ground, is itself not first seen as its correct colour. There appears thus to obtain a certain reciprocity between blue and red with regard to the chromatic space threshold of colours on coloured grounds. If the ground is red it seems to facilitate the chromatic space threshold of blue and largely to dispose the other colours to appear first in the form of blue; while if the ground is blue the favoured colour is red. The significance of this peculiar behaviour will appear later. For the present I record it as a remarkable fact which has come out in the course of our experiments.

(5) Green Ground.—The results on this ground compared with those on the blue or the red ground show a general lowering of the chromatic space threshold of purple, but the lowest threshold again tends to be in red with yellow no. 1 not far off. Orange is somewhat higher than either red or yellow no. 1, while it is lower on the other hand than purple. Yellow no. 2 is only moderately high, slightly above orange. Yellow-green is of course very high, as might be expected from its great similarity to the green ground and the consequent difficulty of distinguishing between them for small sizes of the former. Blue-green likewise tends to be high for the same reason. Blue remains high though always somewhat lower than blue-green. Violet is considerably lower than blue though not as low as purple, except that Mr. Shaw and Mr. Creighton both see it at slightly lower visual angles than purple. In Mr. Shaw's case the angles are

so nearly alike that one cannot say that the deviation from the rule obtaining among the others is not merely an accident of circumstances and due to an unusual condition of his sensibility in some of his observations. Mr. Creighton's deviation also can perhaps scarcely be attributed to any other than accidental causes, for while some six observations by him of each of the two colours, violet and purple, give very similar readings for the former they do not manifest the same consistency in the case of purple, the figures being both higher and lower than any of his readings for violet. The greys stand on a green ground very much as they do on a blue ground, relatively to each other. Grey no. 2 is uniformly for all observers higher in chromatic threshold than grey no. 1.

The peculiar feature which has been noted in regard to the results on other grounds is repeated here, that although a slight lowering of the chromatic space thresholds of colours complementary to the ground may be noticed, yet there is a greater lowering still in the threshold of some other colour—red in the case of blue and green grounds and blue in the case of red ground.

I may mention that in our graphic representation for coloured grounds we have in the case of blue ground (Figs. 10 and 11) given only the curve representing chromatic and achromatic thresholds for one observer, in order that the figure may not be too complicated In the figure for green ground only the characteristic threshold is represented, for the same reason.

Characteristic Thresholds.

(1) Black Ground.—Our characteristic space thresholds on a black ground show a very nice agreement between the various observers. As may be seen by a glance at Section III of Tables I, II, III and IV, and Curve III in Figs. 4, 5 and 6, the lowest space thresholds are respectively those of red, yellow no. 2, and the region of blue and blue-green. On the other hand the spectral regions of highest characteristic space thresholds are orange and orange-yellow (yellow no. 1), yellow-green and violet, which last, however, is not for all observers among the highest. Purple and green have medium thresholds. The results are not exactly in agreement as to the relation of orange and yellow no. 1. Mr. Preston sees orange at a very low threshold, in consonance with his results for chromatic space thresholds on a black ground, from which it appeared that he was very sensitive to orange. Mr. McCallum's results and those of

the mixed observers indicate that the orange threshold for them was higher than the threshold of yellow no. 1. However. we cannot permit either of these to decide the actual threshold relationship of orange and yellow no. 1 in the face of the other two results which reverse the order given by these. For Mr. McCallum's results are for only one set of observations, and although strongly corroborating the other results where agreeing with them, yet where disagreeing with them it cannot be taken as evidence in rebuttal, because subsequent observations might easily have transformed the disagreements into uniformity. A single set of observations could scarcely be free from liability to accidental deviations. There is also a large margin of variability, possible and habitual, in the judgments of every observer on these matters, and it is obvious that to adopt any one of these varying judgments as representing the average of them all is to be in danger of greatly distorting the threshold representation. Hence we cannot put serious emphasis upon the contradiction by Mr. McCallum's results of those of Mr. Preston and Dr. Kirschmann, which are based on the average of several sets of observations. The evidence of the mixed observer's results we cannot consider conclusive against what is shown by the others. I may here remark that these results are a combination of four single sets of observations by four different men, and it is necessary to notice that there was not the same degree of agreement between them that was to be found in the several observations of the same observer. Individual differences in sensibility, accentuated by accidental deviations that are due to unaccustomed conditions for observation and uncorrected by multiplied trials, would be very likely to lead to just such divergences as occur in the regions of orange and yellow no. 1. And yet we would maintain the usefulness of such mixed observations. For although it is not advisable to base upon them a refusal to accept the averaged results of several sets of observations by a single observer, yet where they agree, especially where agreement is throughout the largest part of the results, they constitute excellent corroborative testimony.

The results for grey on black ground show that for two of the observers grey no. 2 is seen, in the final form in which it can be seen at all within the limits of the visual angle of the full diaphragm opening (2° 6′ 55.66″), at a higher mark than grey no. 1. For the other observer they are seen at about an equal marking.

A glance at Curve III of Figs. 4, 5 and 6 will show the coincidence of the different observers in the main. In all three cases we have three marked prominences, a blunt one at the orange and orange-yellow, and a pointed one each in the yellow-green and violet. Between the prominences are depressions in each case, a narrow and pointed one at the yellow (a coincidence of chromatic and characteristic colour threshold), and a wider one from green to blue. Agreement prevails also in the circumstance that the three curves meet each other at the red.

(2) Grey Ground.—On a grey ground the same colours as on a black ground have the lowest thresholds, red, yellow no. 2, blue, and blue-green. There is some difference in regard to the highest markings; yellow no. 1 has alternative readings, one high and another quite low, and the green, which on black ground was a medium colour between high and low in regard to its threshold, has one of the highest thresholds on the grey ground. The explanation of the discrepancy in respect to green and yellow-green is probably to be sought in the fact, that since relatively to the ground there has been a decrease in the intensity of the colours by the loss of brightness contrast, it has become correspondingly difficult to distinguish the green from the yellow-green, and this would result in raising the threshold of green, as is shown in Tables V, VI and VII. A graphic representation is given for two of the observers (Creighton and Dodds) in Curve III of Figs. 7 and 8.

The low alternative threshold of yellow-green may be explained by the passage of a large cloud producing a sudden change in the brightness of the ground, for it will be remembered that we were compelled to have recourse to daylight for the illumination of the grey ground. This darkening of the ground of course effected a relative brightening of the coloured surface, emphasizing its colour quality, especially in the case of our standard yellow-green, which had to be of considerable intensity for the slight yellow element in it to be recognizable.

Another influence besides the one just mentioned assisted in raising the thresholds of the greens. On this ground both green and blue-green generally appeared first as undecidedly bluish or greenish or both combined, and the bluish element clung so long to the green that an observer became disposed to call the colour alternately blue-green and yellow-green. The latter presumably arose from the known indeterminateness of our yellow-green on this ground, combined with the presence in the eye of a negative after-image of the bluish element induced by continuously regarding the coloured surface. I remember quite distinctly in my own observations on green with this grey ground how very difficult it was to see the plain green freed from the strong bluish tinge or its sudden yellowish substitute accelerated by a readjustment of the muscular apparatus of the eye.

There is just such an equivocal relationship between the characteristic thresholds of orange and yellow no. 1; that is, the latter has alternative readings, one high and the other low. The difficulty with all three observers was to distinguish the orange from the yellow. In Mr. Creighton's case the higher marking is probably the more reliable, because his several judgments of the characteristic threshold of yellow no. 1 are prevalently high. Twice out of a total of five observations he does not see it as anything but orange at the full opening of the diaphragm. The lower marking seems to be due to an accidental darkening of the grey ground by a passing cloud, which, of course, effected a relative increase in the brightness of the yellow surface, and thus rendered it more easily distinguishable from orange. For the other two observers, however, the lower markings seem to be the more accurate and representative. Their sensibility is probably somewhat keener than that of Mr. Creighton in the power of distinguishing these two colours from others.

The conclusion, then, that we come to is that the colours having the highest characteristic space threshold on a grey ground are those in the region of orange and yellow no. 1 (with special individual variations), yellow-green and green (with special individual variations), and violet. The lowest points we have already enumerated. The agreement between the results on the grey and those on the black grounds is very generally sustained, but with a considerable enlarging of the thresholds all round on the grey ground as the curves nicely indicate.

(3) Red Ground.—On red ground we find a strikingly unanimous indication that the lowest threshold mark is at blue, and that the colours on both sides of it in the spectrum have increasingly higher thresholds as they are further away from it. (See Tables VIII, IX and X.) This is shown graphically in Fig. 9, Curves III, IV and V, where it is seen not only that the curves are of the same general conformation, but further that they almost come to a point at blue, which is in each case the lowest part of the curve. The

highest marking is reached mainly in orange, yellow-green, violet and purple, while in orange-yellow there is a disposition to decrease, though in no case does it reach the low threshold of blue. The blue-green is for the most part also low. Of the greys, grey no. 2 has the higher characteristic threshold, although théy are not really seen characteristically at all within the limits of full opening of the diaphragm, because the colour induction from the red ground is too strong to disappear within so small a visual angle. (I have not represented the greys at all in the curves.)

It will be noticed that very much the same results as obtained on the black and grey grounds in regard to the highest thresholds obtain on the red ground, yellow-green, orange and violet being still the colours with the highest thresholds. The threshold of purple has been raised, however, on this ground, doubtless from the great similarity between purple and red, which would render them not easily distinguishable.

So far as the lowest threshold points are concerned it would seem that the red ground has not altered the condition of things obtaining on the colourless grounds, except by reducing still more the thresholds of colours in the blue-green and blue region.

It must at once strike us as a peculiar fact that on a *red* ground *blue* should be the colour of lowest characteristic space threshold. We should rather have expected that the blue-green would have taken that place from the fact that it is the so-called complementary of red. According to the rules of colour contrast a colour induces upon any contiguous or neighbouring surface its own complementary. Hence, we should expect, on account of the accentuation of the blue-green colour quality by contrast induction from the red ground, that the blue-green would display a marked superiority in the ease with which it makes itself distinguishable at small angular sizes. The influences at play we should expect to be doubly in favour of the early and small-sized threshold of blue-green. For not only is there a positive influence emphasizing the peculiar colour quality of blue-green itself, but there is equally a retarding influence upon every other colour in the form of a blue-green induction, which we must suppose to obscure to some degree their proper colour quality, and to render their definite discernment correspondingly difficult. However, the facts as shown in our experimental results are arrayed against our expectations in this case, and we find as in the case of the chromatic and achromatic space thresholds that the red ground does not apparently facilitate its complementary blue-green in characteristic colour perceptibility according to size, to such a degree as it does another colour which is not its complementary, viz. blue.

(4) Green Ground.—The results on a green ground were somewhat peculiar in several ways. The lowest threshold marking was that of red, as is shown in our Tables XI, XII, XIII, XIV and XV, and in the curves of Fig. 10. Purple is low and in one instance (Mr. Dodds' observations) its threshold magnitude is the same as that of red. Blue also is comparatively low. In fact red, blue and purple, with the two greens (yellow-green and blue-green), which are high in threshold, are the only colours which really had any characteristic colour thresholds at all on the green ground. The curve representation (Fig. 10) indicates not really the characteristic space thresholds for the other colours, but the angular magnitudes at which they were first seen in the final form of their appearance at full opening of the diaphragm aperture. For example, the thresholds for orange in these curves indicate the various points at which orange first appeared as red or purple or orange-red, as the case may have been for the several observers. Yellow no. 1 was seen as orange or orange-red, and yellow no. 2 as orange or orange-yellow. Even yellow-green appeared generally as a yellow-grey and violet either as simply purple or as purple with a slight tinge of violet. Grey no. 2 is uniformly higher than grey no. 1 on this ground in their final form, though strictly they have no characteristic space threshold on this ground.

It will be noticed that although there has been a lowering in the characteristic space threshold of the complementary of green, yet there is another colour, red, whose characteristic space threshold is still lower.

(5) Blue Ground.—By reference to Tables XVI, XVII, XVIII, XIX, XX, and to Fig. 11, we see that on a blue ground the lowest characteristic space threshold is quite decisively that of red. Just as in the case of the red ground at the blue, so here at the red, the curves almost come to a point, which is moreover by far the lowest point. The colours of next lowest characteristic space threshold are respectively purple and yellow-green. The highest points are reached by orange, blue-green, green and the two yellows. In fact orange and the yellows have

scarcely characteristic space thresholds at all within the limits of the full diaphragm aperture, whose visual angle was 2° 6′ 55.66″. Orange is never seen as orange except by one observer, and even with him it was more red than orange. It uniformly appears as red, or red with a very faint tinge of orange. Yellow no. 1 is usually seen as orange-red and yellow no. 2 as orange-yellow. Green is mostly though not always seen as yellow-green and blue-green as plain green. Violet is almost always either purple or red, with a tinge of violet in both cases, only one observer in a few observations making it out as a reddish violet. On this ground the greys were not seen of their proper tone at all. In their final form within the circumscribed limits of largest diaphragm aperture grey no. 1 appeared as orange-yellow and grey no. 2 as "dirty" yellow.

We might be disposed to explain these modifications in our standard colour tones on the blue ground (and on the green ground also as before noted) by saying that the blue ground induces upon the colours an orange-yellow element, which obscures the bluish element in the blue-green (both the saturation contrast of the blue ground and the blue element in the blue-green working in the same direction), makes the green appear yellowish, makes the yellow appear orange, etc. This explanation may hold for the other colours but to orange itself it does not at first sight apply. For we should not expect that the mere accentuation of the orange quality in orange would convert it into another colour, red, instead of effecting an increase in its saturation as orange. However the former is what actually occurs, at least within the limits of the full aperture of the diaphragm. It is futile to seek to explain away this conversion of orange into red at small sizes by supposing that it is due to some minor irregularities in the *fovea centralis*. If such were the case we should expect that so soon as the diaphragm opening was enlarged orange would reappear in place of red. But it does not; the orange remains red and not orange up to the fullest opening of the diaphragm (2° 6′ 55.66″). It appears therefore that this notable phenomenon is not a trifling irregularity of a very limited retinal area but is more probably a property of colour phenomena which must be recognized and reckoned with in any adequate theory of colours. Any explanation like the above, for such a theory as Hering's, which must assume the ordinary complementary relations of the colours to hold at all hazards, would seem to emphasize a factor to which component theories of all kinds have paid but little attention, namely, saturation as an independent variable of light phenomena of equal importance with light intensity and colour tone. It would seem indeed as though there must be here admitted a dependency of colour tone on saturation, somewhat akin to the dependency of colour tone upon light intensity which is called the phenomenon of Purkinje*, or else a violation of the inviolable complementary relationships of the colours. In other words, blue must induce not orange but red, or else the increased saturation of the orange quality leads to a change of its colour tone. It has been found that a considerable change in the brightness intensity of a coloured surface, whether by way of increase or decrease, tends to alter the character of the colour tone; it appears to be equally true that at small visual angles, at least, it is possible to produce a change in colour tone by varying only the saturation intensity while the light intensity remains constant. For those who maintain the component theories of colours this seems to be the only alternative to the admission that two colours may act as complementaries at large angular sizes of exposed surfaces which do not at small visual angles. This latter alternative would of course introduce anarchy and confusion into such a system of balanced complementary constituents as Hering's theory assumes.

But however we may get over the difficulty of explaining the above phenomena on the principles of a component theory, we are still confronted with another phenomenon, which has been cropping out in all our experimental results for the three thresholds. This is not the difficulty of a complementary ground producing a changed tone in one particular colour and an obscuration in others, but that some colour other than the complementary of the ground is seen earlier than the complementary, *i.e.*, at smaller visual angles, at once achromatically, chromatically and characteristically. We notice the same phenomenon with the blue ground as was remarked in the case of the other coloured grounds, namely, that not the complementary, orange, has the lowest characteristic space threshold, but red. If we consider the blue and red grounds together it will be seen that blue and red act much more as complementaries in this matter of space thresholds than do either blue and orange or red and blue-green, the colours which are ordinarily designated complementaries. The blue ground seems to facilitate the minute percepti-

* Kirschmann's "Colour Saturation and its Quantitative Relations." (American Journal of Psych., vol. viii., p. 394.)

bility of red (both as coloured and as properly coloured) rather than the other colour elements, and the red ground acts similarly upon the blue. We should naturally expect that on a blue ground orange would have the lowest characteristic threshold, but, so far from this being the case, it scarcely has any characteristic threshold at all within the limits of 2° 6′ 55.66″; and on the red ground not the blue-green but the blue is the lowest in characteristic space threshold. What may be the significance of this balanced mutuality of behaviour between blue and red, it is perhaps not in our power to demonstrate. But it would appear that there is a disturbance of the ordinary complementary relationships of the various members of the colour system when the colour surfaces exposed are reduced to small visual angles.

Whatever the real explanation of the fact, it is interesting to note that there is on record a case of monocular colour-blindness in which blue and red were the only elements in the colour system, and that they acted towards each other like ordinary complementaries, just as in our space threshold experiments. The case was investigated by Dr. Kirschmann in the Leipzig Laboratory, and is recorded in his article "Beiträge zur Kenntnisse des Farbenblindheit."* It is the case of Professor A. (numbered case five of the beforementioned article), a man whose left eye was perfectly normal in its colour sensibility, but whose right eye was a dichromate colour-blind, having only blue and red as the foundation of its colour system. The irregularity in the right eye was congenital, and not produced by any accident or disease, as is evident from the fact that some other members of his family were organized very much in the same way. Experiments were carefully made with the spectroscope for the two eyes independently, and it was found that while the left eye was quite normal in its appreciation of the various colours, the right eye was capable of distinguishing only red and blue; all the other colours were seen as various saturations of one or other of these. Orange, for example, as in our space threshold experiments on a blue ground, was seen as red. Careful after-image tests were made with spectral colours, and not only was the colour system for the abnormal eye one-dimensional, based on blue and red, but the blue and red acted throughout as complementaries. Each spectral colour seen as red left a blue negative after-image, and *vice versa*.

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*Philos. Studien, vol. viii, p. 199.

Such a condition of things was, of course, rather remarkable, both because of the fact that the one eye was perfectly normal in its appreciation of colours and because the impaired sensibility of the colour-blind eye showed neither more nor less than normal appreciation for red and blue, while at the same time these two colours acted as complementaries. Such an unorthodox behaviour on the part of this colour-blind eye was quite in contravention of the component theories of colour, and among the adherents of the component theories there was a disposition to deny the accuracy of the experiments,* to minimize the importance of the facts disclosed, or even to ignore them altogether. For it is plain that if white light is composed of three constituent colour elements, red, blue and green, as the Young-Helmholtz theory assumes, it is inexplicable how this colour-blind eye could see colourless light at all, having sensibility for only two of the three, red and blue. Again, if red is a sensation which arises from the destruction of a certain kind of visual substance, and blue a sensation arising from the construction of a totally different kind of visual substance, as Hering's theory propounds, it is inexplicable how this particular colour-blind eye could continue long to have sensi bility for more than blue alone. For the blue and red of this abnormal eye are exactly the same as those colours in the normal eye, as was shown by careful test. Hence the destruction of the red substance could never be made up by the construction of the blue, since according to the theory they are totally different, with the inevitable result that the red substance must ultimately become exhausted, and, *eo ipso*, the appreciation of red be destroyed. There is no obvious way of adroitly escaping from the difficulty by supposing this a special case where the red and blue are the dissimilative and assimilative aspects of the same visual substance, because this is to assume that red and blue for this eye are different from red and blue for the normal eye, which was experimentally shown not to be the case.

My object in referring to Dr. Kirschmann's paper is to call attention to the remarkable coincidence between the colour sensi-

*Professor Ebinghaus shows this attitude toward the matter in his article on p. 215, Band v, of the *Zeitschrift für Psychologie*. The importance of the above case of colour-blindness can scarcely be set aside in the summary way that Professor Ebinghaus is disposed to use. The observations and experiments were not only carefully and accurately conducted, but Professor A. was an expert opticist, and thoroughly competent to judge the facts presented to him.

bility for blue and red in this colour-blind dichromate and our space threshold results. I have frequently in this paper laid stress on the fact disclosed in our results that coloured grounds do not seem to lower the space threshold of their ordinary complementaries so much as they do that of some other colours, as red and blue. We have noticed that on red ground almost all the colours appear first as blue, and on blue nearly all appear first as red, including even the complementaries themselves of the coloured grounds. We have also noticed that in regard to characteristic space thresholds there appears to be the same disturbance of the ordinary complementary relationships of the colour system as in the other thresholds, and that the evidence for it is even more emphatically unanimous. In our experiments for determining space thresholds red and blue seem to act exactly as complementaries might be expected to act.

It thus appears, so far as our experiments go, that for small angular sizes of coloured surfaces there is a disturbance of ordinary complementary relations, and that for red and blue grounds at small visual angles a condition of things obtains which is somewhat similar to that present in the colour-blind eye of Professor A. The coincidence is not quite complete because there is not absolute failure to appreciate other colour qualities besides red and blue. I would enunciate our conclusions on this question in the following way :—On red and blue grounds, below the limits of the characteristic space thresholds of blue and red respectively, there is a lack of ability in the normal eye to make definite discriminations of the other spectral colour tones and a tendency to confuse them with either red or blue. Thus in a limited sphere embracing only small angular sizes are practically reproduced the conditions of colour sensibility exhibited by the colour-blind eye of Professor A., which form a colour system of one dimension founded on the two colours red and blue.

Further, it is interesting to note that in this peculiar complementary relation between blue and red we have come across what in our estimation is a formidable difficulty to Hering's colour theory, by which all colour phenomena are explained by a threefold antagonism of fundamental colour processes. Black, red and yellow are by him set over against white, green and blue respectively, the former three being the outcome of the destruction of three distinct kinds of visual substance, while the corresponding latter three are the outcome of the construction or assimilation of the same kinds of nervous substance respectively. A complementary relation of colours is inherent in the nature of the optical organism and is the issue of the natural balanced activity of fatigue and repair, destruction of tissue and consequent recuperation. The different sets of complementaries belong to the activity of the different kinds of visual substance. From this theory it would follow that the red process set up in the optical apparatus should originate the green process in a contiguous surface relieved from the stimulation of the red. Applied in particular to our course of experiments we should expect that the red ground, when watched for the emergence at its centre of a small surface differently qualified, would tend to induce upon the emerging surface a green colour. The theory apparently demands so much by its physical resolution of the phenomena of complementary relationships, rendering them rigid and inviolable. But the facts of the case as shown in our experiments are that the red does not induce green but blue. And it appears to us that this actual disturbance of the complementary relationships is a difficulty which Hering's theory is utterly unable to account for.

It might be offered as a plausible explanation from Hering's point of view, and according to his terminology, that the matter is an aspect of irradiation or light induction or negative contrast, by which is meant that a coloured surface tends not merely to induce upon a contiguous surface its complementary colour but also to spread its own peculiar colour quality over it. But our rejection of such an explanation is unqualified. In the first place, if the red tends not only to induce green upon the surface revealed by the opening aperture of the diaphragm but also to irradiate a positive influence of red itself, we are no nearer an explanation than before, having on our hands a weakened saturation of induced green instead of the blue which we wished to explain. For it follows that if the negative induction assumed is slight and not quantitatively equal to the green induced, then as far as it goes it will neutralize the colour quality of some of the green induced, and produce colourless light. This, which is a strict deduction from the theory, would still leave a weak saturation of green and not blue, because of the admixture of the colourless light and the residue of green. Again, if the negative induction is equal in quantity to the green induction, we should have no colour induction at all but simply an induction of colourless light, which is as little like blue as ever. Finally, if we admit the inadmissible, that some different colour result than green could be produced in such a case according to the strict letter of Hering's theory, then we must demand what reason can be shown why the negative induction should lead to a compromise result on the blue side of green instead of on the yellow. There is just as much reason *a priori* for one as for the other, and the fact that the blue is actually the one induced is indicative that there must be some reason beyond the scope of the explanations that the Hering theory can offer. There is a certain so-called parsimony in nature, but scientists must not outstrip nature in parsimony to such a degree as to make everything in nature fit to a few cramped or Procrustean explanations, which have the advantage of brevity and clearness but at the expense of exactness.

Table I.—On Black Ground.

Observer: Dr. Kirschmann.

Colour.	I. Achromatic threshold.					II. Chromatic threshold.					III. Characteristic colour threshold.					Remarks.
	Diagonal of diaphragm opening in 1000ths of aninch.	Visual angle of diameter of diaphragm opening.		Visual angle of diagonal of diaphragm opening.		Diagonal of diaphragm opening in 1000ths of an inch.	Visual angle of diameter of diaphragm opening.		Visual angle of diagonal of diaphragm opening.		Diagonal of diaphragm opening in 1000ths of an inch.	Visual angle of diameter of diaphragm opening.		Visual angle of diagonal of diaphragm opening.		
		′	″	′	″		′	″	′	″		′	″	′	″	
Purple..........	36⅙	1	17.9	1	50.16	78⅔	2	49.44	3	59.61	154⅓	5	32.41	7	50.1	
Red..........	57	2	3.77	2	53.62	57	2	3.77	2	53.62	82	2	56.62	4	9.77	
Orange..........	45⅙	1	39.28	2	17.58	71⅙	2	33.28	3	36.77	409⅓	14	41.64	20	46.82	
Yellow..........	38⅓	1	22.56	1	56.76	77⅓	2	47.28	3	56.52	456⅚	16	23.95	23	11.51	
Yellow II.......	30	1	4.62	1	31.38	104	3	44.	5	16.82	104	3	44.	5	16.82	
Yellow-green....	42⅓	1	31.54	2	9.46	86⅚	3	7.02	4	24.49	288	10	20.3	14	39.	
Green..........	32⅔	1	10.36	1	39.52	100⅓	3	36.1	5	5.61	167⅔	6	1.13	8	30.71	
Blue-green......	24⅓		52.41	1	14.1	70⅓	2	31.49	3	34.23	113⅔	4	4.82	5	46.23	
Blue..........	22¾		49.01	1	9.3	82	2	56.62	4	9.77	133	4	46.46	6	45.12	
Violet..........	25	1	16.1	2	3.3	84	3	0.92	4	15.86	313½	11	15.23	15	54.92	Poorer violet outside than out at full.
Grey I..........	24		51.69	1	13.11	62⅓	2	14.22	3	9.87	70	2	30.77	3	33.22	
Grey II.........	37⅓	1	20.41	1	53.72	114⅚	4	7.93	5	49.78	489⅓	17	33.95	24	50.5	

Table II.—On Black Ground.

Observer : Mr. Preston.

Colour.	I. Achromatic threshold.					II. Chromatic threshold.					III. Characteristic colour threshold.					Remarks.
	Diagonal of diaphragm opening in 1000ths of an inch.	Visual angle of diameter of diaphragm opening.		Visual angle of diagonal of diaphragm opening.		Diagonal of diaphragm opening in 1000ths of an inch.	Visual angle of diameter of diaphragm opening.		Visual angle of diagonal of diaphragm opening.		Diagonal of diaphragm opening in 1000ths of an inch.	Visual angle of diameter of diaphragm opening.		Visual angle of diagonal of diaphragm opening.		
		′	″	′	″		′	″	′	″		′	″	′	″	
Purple..........	$27\frac{2}{5}$		59.	1	23.46	$61\frac{1}{3}$	2	12.1	3	6.8	$1294\frac{4}{5}$	4	39.57	6	35.4	
Red	$55\frac{1}{5}$	1	58.9	2	48.14	$55\frac{1}{5}$	1	58.9	2	48.14	$55\frac{1}{5}$	1	58.9	2	48 14	
Orange	$44\frac{2}{5}$	1	35.64	2	15.2	$44\frac{2}{5}$	1	35.64	2	15.2	$132\frac{4}{5}$	4	46.	6	44.5	
Yellow I........	$31\frac{1}{5}$	1	7.2	1	35.04	$54\frac{3}{5}$	1	49.74	2	46.32	$719\frac{1}{5}$	25	49.04	37	10.66	
Yellow II.	$30\frac{1}{5}$	1	5.06	1	31.8	47	1	41.24	2	23.16	$196\frac{9}{10}$	7	2.2	9	59.74	
Yellow-green	$33\frac{2}{5}$	1	11.94	1	41.74	50	1	47.7	2	32.26	699	25	5.54	35	30.94	
Green	$29\frac{2}{5}$	1	3.32	1	27.56	$50\frac{1}{5}$	1	48.12	2	32.9	$304\frac{4}{5}$	10	56.48	15	28.4	
Blue-green	$24\frac{2}{5}$		52.56	1	14.32	$37\frac{3}{5}$	1	20.52	1	53.9	$223\frac{3}{5}$	8	1.6	11	21.1	
Blue............	......	...	...	...	...	......	...	...	...	...	......	...	...	...	...	
Violet	25		53.84	1	16.14	$37\frac{4}{5}$	1	21.42	1	55.14	$187\frac{1}{5}$	6	43.2	9	30.22	
Grey I..........	$24\frac{2}{5}$		52.58	1	14.32	$51\frac{2}{5}$	1	50.97	2	36.57	$236\frac{1}{3}$	8	31.6	11	59.8	
Grey II.	$28\frac{2}{5}$	1	1.6	1	27.12	$59\frac{1}{4}$	2	7.62	3	0.48	$225\frac{3}{4}$	8	6.23	11	27.64	

Table III.—On Black Ground.

Mixed Observers (4 averaged).

Colour.	I. Achromatic threshold.					II. Chromatic threshold.					III. Characteristic colour threshold.					Remarks.
	Diagonal of diaphragm opening in 1000ths of an inch.	Visual angle of diameter of diaphragm opening.		Visual angle of diagonal of diaphragm opening.		Diagonal of diaphragm opening in 1000ths of an inch.	Visual angle of diameter of diaphragm opening.		Visual angle of diagonal of diaphragm opeding.		Diagonal of diaphragm opening in 1000ths of an inch.	Visual angle of diameter of diaphragm opening.		Visual angle of diagonal of diaphragm opening.		
		′	″	′	″		′	″	′	″		′	″	′	″	
Purple	38⅝	.....	.....	1	58.2	56⅓	2	2.	2	52.	234	8	24.	11	52.77	
Red	34¼	1	13.77	1	44.33	34¼	1	13.77	1	44.33	34¼	1	13 77	1	44.33	
Orange	42⅞	.....	.....	2	10.6	65¼	2	20.54	3	18.75	355	12	46 8	18	1.4	
Yellow I.	40⅜	1	26.96	2	2.99	83⅞	3	0.76	4	15.48	279⅔	10	2.	14	11.	
Yellow II.	40	1	26.16	2	1.84	156	5	36.	7	55.18	156	5	36.	7	55.18	
Yellow-green	32¼	1	9.47	1	38.24	114⅛	4	5.81	5	47.63	465	16	41.44	23	36.39	
Green	34⅛	1	13 5	1	43.94	71⅝	2	34 27	3	38.17	136½	4	54.	6	55.78	
Blue-green	31	1	6.79	1	34.43	68	2	26.46	3	37.13	121¼	4	21.16	6	8.73	
Blue	31⅔	1	8.21	1	36.46	115⅓	4	8.41	5	51.3	161	5	46.6	8	10.	
Violet	32¼	1	9.47	1	38.24	59¼	2	7.62	3	0.48	316½	11	20.69	16	4.06	
Grey I.	32	1	8.93	1	37.48	93	3	20.31	4	43.28	323	11	35.69	16	23.86	
Grey II.	32	1	8.93	1	37.48	139	4	59.39	7	3.40	370⅓	13	17.64	18	48.04	

Table IV.—On Black Ground.

Observer: Mr. McCallum.

Colour.	I. Achromatic threshold.			II. Chromatic threshold.			III. Characteristic colour threshold.			Remarks.
	Diagonal of diaphragm opening in 1000ths of an inch.	Visual angle of diameter of diaphragm opening.	Visual angle of diagonal of diaphragm opening.	Diagonal of diaphragm opening in 1000ths of an inch.	Visual angle of diameter of diaphragm opening.	Visual angle of diagonal of diaphragm opening.	Diagonal of diaphragm opening in 1000ths of an inch.	Visual angle of diameter of diaphragm opening.	Visual angle of diagonal of diaphragm opening.	
		′ ″	′ ″		′ ″	′ ″		′ ″	′ ″	
Purple	40	1 27.6	2 1.8	64	2 14.6	3 14.8	281	10 11.6	14 25.	
Red	36	1 17.6	1 49.6	36	1 17.6	1 49.6	36	1 17.6	1 49 6	
Orange	42	1 30.4	2 7.9	90	3 13.8	4 35.2	588	21 6.4	29 51.	
Yellow I	44	1 34.6	2 14.	139	4 59.4	7 13.4	477	17 7.2	24 13.	
Yellow II	40	1 26.16	2 1.84	156	5 36.	7 55.18	156	5 36.	7 55.18	
Yellow-green	31	1 6.8	1 34.4	136½	4 54.	6 55.8	458	16 26.	23 15.	
Green	28	1 0.2	1 25.2	94	3 22.4	4 46.2	181	6 29 8	9 11.	
Blue-green	20	43.	1 0.8	96	3 27.8	4 52.4	177½	6 22.	9 0.	
Blue	28	1 0.2	1 25.2	161	5 46.6	8 10.4	161	5 46.6	8 10.4	
Violet	25	53.8	1 16.	72	2 35.	3 39.2	550	19 44.6	27 55.2	

Representation of the Space-Thresholds for Black Ground.

Scale : 1 inch = 10 minutes.
Curve I—Achromatic Threshold,
" II—Chromatic Threshold,
" III—Characteristic Colour Threshold.

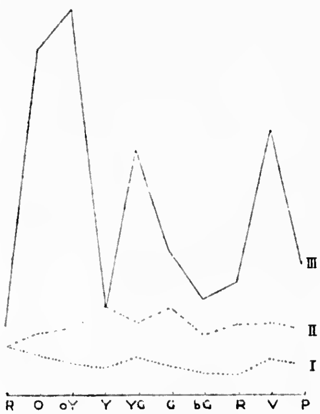

Fig. 4 (Table I).

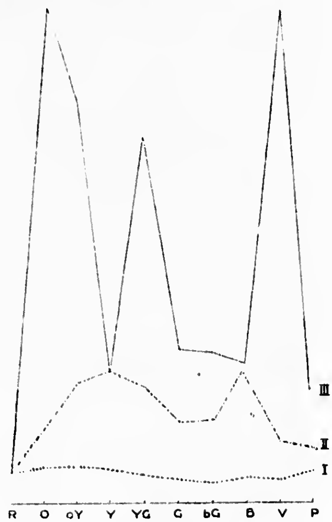

Fig. 5 (Table II).

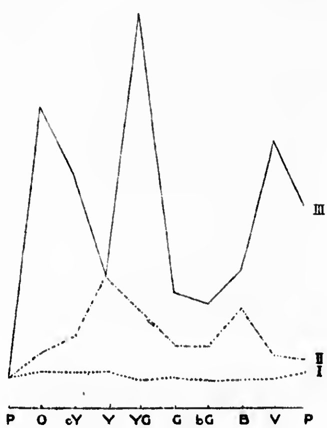

Fig. 6 (Table III).

Table V.—On Grey Ground.

Observer: Mr. Creighton.

Colour.	I. Achromatic threshold.		II. Chromatic threshold.		III. Characteristic colour threshold.		Remarks.
	Diagonal of diaphragm opening in 1000ths of an inch.	Visual angle of diagonal of diaphragm opening.	Diagonal of diaphragm opening in 1000ths of an inch.	Visual angle of diagonal of diaphragm opening.	Diagonal of diaphragm opening in 1000ths of an inch.	Visual angle of diagonal of diaphragm opening.	
		′ ″		′ ″		′ ″	
Purple	$71\frac{3}{8}$	3 37.3	$103\frac{7}{8}$	5 16.3	205	10 24.45	
Red	$41\frac{3}{4}$	2 7.15	$74\frac{1}{4}$	3 46.15	129	6 33.	
Orange	$55\frac{1}{2}$	2 49.	$71\frac{9}{10}$	3 39.	$1036\frac{1}{2}$	52 37.12	
Yellow I.	$73\frac{1}{5}$	3 42.95	$82\frac{3}{5}$	4 14.7	1347 (105)	1° 8 22.94 (5′ 19.8″)	
Yellow II.	$48\frac{3}{8}$	2 27.2	$59\frac{1}{8}$	3 0.	$81\frac{1}{4}$	4 7.46	Seen twice at full as plain green only.
Yellow-green	$57\frac{2}{5}$	2 54.8	$78\frac{1}{5}$	3 58.1	$678\frac{1}{3}$	34 27.92	
Green	$51\frac{1}{2}$	2 36.86	73	3 42.4	1341	1° 8 4.66	
Blue-green	$53\frac{1}{8}$	2 41.8	$85\frac{7}{8}$	4 21.55	$128\frac{1}{5}$	6 31.5	
Blue	$48\frac{2}{3}$	2 28.	$110\frac{3}{4}$	5 37.3	$250\frac{3}{4}$	12 43.73	
Violet	$44\frac{1}{2}$	2 15.5	75	3 48.4	$615\frac{2}{3}$	31 15.3	

Table VI.—On Grey Ground.

Observer: Mr. Dodds.

Colour.	I. Achromatic threshold.			II. Chromatic threshold.			III. Characteristic colour threshold.			Remarks.
	Diagonal of diaphragm opening in 1000ths of an inch.	Visual angle of diagonal of diaphragm opening.		Diagonal of diaphragm opening in 1000ths of an inch.	Visual angle of diagonal of diaphragm opening.		Diagonal of diaphragm opening in 1000ths of an inch.	Visual angle of diagonal of diaphragm opening.		
		′	″		′	″		′	″	
Purple	79¾	4	2.86	99⅙	5	2.	225	11	24.4	Sometimes seen purple-orange.
Red	58	2	56.66	58	2	56.66	130¼	6	33.7	
Orange	70	3	33.2	74¼	3	46.16	109¼ (631⅓)	5	32.8 (33′ 33.6″)	
Yellow I.	80¾	4	5.93	87⅕	4	26.5	225	11	24.4	
Yellow II	71	3	36.3	77¾	3	56.75	104½	5	17.25	
Yellow-green	79	4	0.53	83	4	12.86	406⅝ (512½)	20	39.2 (26′ 7.4″)	
Green	73¼	3	45.1	73¼	3	45.1	407⅓	20	41.24	
Blue-green	70	3	33.2	74½	3	46.9	160¾	8	9.65	
Blue	62	3	8.9	87¼	4	25.7	135½	6	52.75	
Violet	74	3	45.3	89½	4	32.6	465	23	36.39	

Table VII.—On Grey Ground.

Observer: Mr. W. B. Lane.

Colour.	I. Achromatic threshold.		II. Chromatic threshold.		III. Characteristic colour threshold.		Remarks.
	Diagonal of diaphragm opening in 1000ths of an inch.	Visual angle of diagonal of diaphragm opening.	Diagonal of diaphragm opening in 1000ths of an inch.	Visual angle of diagonal of diaphragm opening.	Diagonal of diaphragm opening in 1000ths of an inch.	Visual angle of diagonal of diaphragm opening.	
		′ ″		′ ″		′ ″	
Purple	65 3/4	3 20.26	75 1/3	3 49.9	242 1/[illegible]	12 17.9	
Red	43 7/12	2 12.75	52 1/4	2 39.1	86 3/10	4 22.8	
Orange	55 2/7	2 49.7	58	2 56.66	535 3/4	27 12.	
Yellow I	58 5/7	2 58.8	65 6/7	3 20.53	(1233 1/5) 257 5/6	(1° 2′ 36.2″) 13 2.26	
Yellow II	56 2/5	2 51.46	67 3/8	3 25.25	181 3/5	9 13.1	
Yellow-green	69 5/14	3 31.	77 9/14	3 56.46	(1459 2/3) 307 1/2	(1° 14′ 6.06″) 15 15.22	
Green	69 5/7	3 32.3	74	3 45.35	603 1/3	30 37.74	
Blue-green	66 1/2	3 22.5	86	4 21.9	132 1/8	6 42.45	
Blue	51 1/6	2 36.86	61 1/3	3 7.33	146 2/3	7 26.73	
Violet	64 3/5	3 16.8	67 3/4	3 26.33	426	21 37.66	

REPRESENTATION OF THE SPACE-THRESHOLDS FOR GREY GROUND.

Scale: 1 inch = 20 minutes.
Curve I—Achromatic Threshold.
" II—Chromatic Threshold.
" III—Characteristic Colour Threshold.

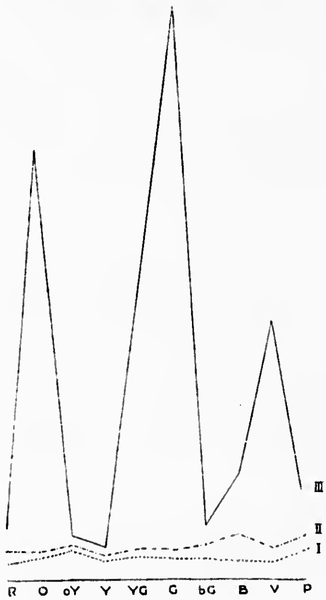

FIG. 7 (Table V).

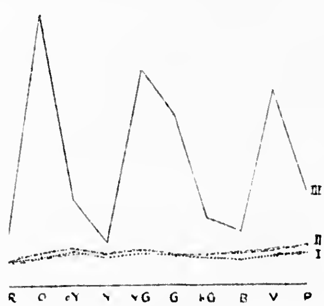

FIG. 8 (Table VI).

Table VIII.—On Red Ground.

Observer: Dr. Kirschmann (left eye).

Colour.	I. Achromatic threshold.		II. Chromatic threshold.		III. Characteristic colour threshold.		Remarks.
	Diagonal of diaphragm opening in 1000ths of an inch.	Visual angle of diagonal of diaphragm opening.	Diagonal of diaphragm opening in 1000ths of an inch.	Visual angle of diagonal of diaphragm opening.	Diagonal of diaphragm opening in 1000ths of an inch.	Visual angle of diagonal of diaphragm opening.	
Purple	307	15′ 35.14″	307	15′ 35.14″	487	24′ 43.4″	Seen first coloured bluish.
Orange	86	4′ 21.93″	137	6′ 57.3″	963	48′ 53.32″	" " "
Yellow I	68½	3′ 28.6″	134	6′ 48.13″	577	29′ 17.58″	" " bluish-grey.
Yellow-green	77	3′ 54.5″	102½	5′ 12.2″	600	30′ 27.6″	" " bluish.
Green	61½	3′ 7.36″	103	5′ 13.7″	415	24′ 4.12″	" " blue.
Blue-green	66½	3′ 22.5″	108	5′ 29.6″	247	12′ 32.39″	" " "
Blue	55½	2′ 49.05″	171	8′ 40.85″	171	8′ 40.85″	" " "
Violet	77	3′ 54.5″	136½	6′ 55.8″	335	17′ 0.44″	
Grey I	64	3′ 14.95″	295	14′ 58.6″	1230	49′ 36.″	
Grey II	64	3′ 14.95″	124	6′ 17.75″	1336½	1° 7′ 33.6″	

Table IX.—On Red Ground.

Observer: Dr. Kirschmann (right eye).

Colour.	I. Achromatic threshold. Diagonal of diaphragm opening in 1000ths of an inch.	I. Visual angle of diagonal.	II. Chromatic threshold. Diagonal of diaphragm opening in 1000ths of an inch.	II. Visual angle of diagonal.	III. Characteristic colour threshold. Diagonal of diaphragm opening in 1000ths of an inch.	III. Visual angle of diagonal.	Remarks.
		′ ″		′ ″		° ′ ″	
Purple	247 3/5	12 32 44	421 4/5	21 24.82	799 3/5	40 35.56	
Orange	122 1/5	6 12.36	154 2/5	7 50.	1880 4/5	1 35 21.56	Seen first coloured bluish.
Yellow I	88 3/5	4 29.36	157 2/5	7 59.44	1082 3/5	54 57.52	" " "
Yellow-green	83 1/5	4 13.42	154 3/5	7 50 9	(713)	(35 41.32)	" " " and at full opening plain green.
Green	77 1/10	3 54.84	161	8 10.4	966 3/4	49 4.68	Seen first coloured bluish.
Blue-green	80	4 3.68	160 1/5	8 8.	382	19 31.64	" " "
Blue	75 3/4	3 50.66	111 3/8	5 39.	179 7/10	9 7.36	" " "
Violet	87	4 25.	196 1/6	9 58.54	484 3/10	24 35.18	" " "
Grey I	73	3 42.36	....	....	1725 1/3	1 27 35.096	Seen at full as yellowish-grey.
Grey II	73 4/5	3 44.75	121 2/3	4 7.74	....	....	Seen first coloured blue.

Table X.—On Red Ground.

Mixed observers (10).

Colour.	I. Achromatic threshold. Diagonal of diaphragm opening in 1000ths of an inch.	I. Visual angle of diagonal of diaphragm opening. ′	″	II. Chromatic threshold. Diagonal of diaphragm opening in 1000ths of an inch.	II. Visual angle of diagonal of diaphragm opening. ′	″	III. Characteristic colour threshold. Diagonal of diaphragm opening in 1000ths of an inch.	III. Visual angle of diagonal of diaphragm opening. °	′	″	Remarks.
Purple	$98\frac{3}{20}$	3	57.48	$295\frac{1}{7}$	14	59.	$1027\frac{2}{9}$		52	8.86	
Orange	$68\frac{7}{10}$	3	29.26	$191\frac{1}{8}$	9	42.51	$1270\frac{1}{7}$	1	4	30.06	
Yellow I	$68\frac{11}{12}$	3	29.92	214	10	51.84	$1143\frac{1}{5}$		58	2.12	
Yellow-green	$61\frac{8}{11}$	3	8.02	$159\frac{1}{3}$	8	5.33	1607	1	21	34.6	
Green	$58\frac{3}{5}$	2	58.5	$163\frac{1}{16}$	8	16.8	$816\frac{5}{8}$		41	27.4	Seen first coloured prevalently as blue.
Blue-green	$58\frac{15}{22}$	2	58.74	$161\frac{11}{16}$	8	13.5	$775\frac{1}{5}$		35	31.2	" " " "
Blue	$56\frac{13}{22}$	2	56.36	$160\frac{1}{2}$	8	8.9	$399\frac{2}{5}$		20	16.6	" " " "
Violet	$58\frac{1}{20}$	2	55.8	$177\frac{3}{5}$	9	0.96	$1010\frac{1}{32}$		51	16.55	" " blue.
Grey I	$57\frac{19}{24}$	3	53.14	$130\frac{10}{11}$	6	38.75	$1399\frac{1}{3}$	1	11	2.74	At full as greyish-yellow.
Grey II	$53\frac{3}{5}$	2	43.27	$134\frac{1}{2}$	6	48.69	$1873\frac{1}{4}$	1	35	5.57	At full as greenish-grey.

Representation of the Space-Thresholds for Red Ground.

Scale: ¾ of an inch = 20 minutes.

Curves I (dotted lines) = Achromatic Threshold.
" II (lines composed of alternate dashes and dots) = Chromatic Threshold
Curve III—Characteristic C. Th. for Observer K.'s left eye (Table VIII).
" IV— " " " " right eye (Table IX).
" V— " " for 10 observers averaged (Table X).

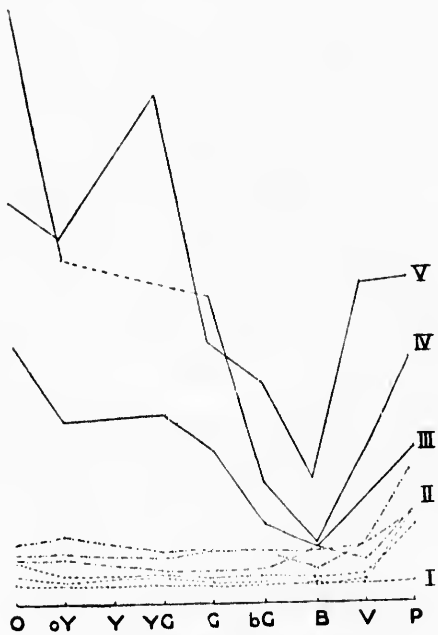

Fig. 9 (Tables VIII, IX and X).

Table XI.—On Green Ground.

Observer: Mr. Creighton.

Colour.	I. Achromatic threshold. Diagonal of diaphragm opening in 1000ths of an inch.	I. Visual angle of diagonal of diaphragm opening. ′	″	II. Chromatic threshold. Diagonal of diaphragm opening in 1000ths of an inch.	II. Visual angle of diagonal of diaphragm opening. ′	″	III. Characteristic colour threshold. Diagonal of diaphragm opening in 1000ths of an inch.	III. Visual angle of diagonal of diaphragm opening. °	′	″	Remarks.
Purple	41	2	4.86	79	4	0.53	$227\frac{1}{5}$		11	32.04	
Red	25	1	17.36	$67\frac{1}{6}$	3	24.6	$90\frac{1}{5}$		4	34.4	Seen purple and red at full.
Orange	$36\frac{1}{3}$	1	50.6	$77\frac{5}{8}$	3	56.9	$310\frac{4}{5}$		15	45.	
Yellow I	$38\frac{3}{4}$	1	57.9	$75\frac{3}{4}$	3	50.7	$1296\frac{2}{3}$	1	5	49.51	Seen orange at full.
Yellow II	$40\frac{1}{5}$	2	5.09	$85\frac{2}{5}$	4	20.1	$530\frac{2}{3}$		26	56.4	
Yellow-green	$41\frac{3}{4}$	2	7.09	163	8	16.46	1965	1	39	45.2	Seen violet-green at full.
Blue-green	$65\frac{3}{5}$	3	19.8	$157\frac{1}{2}$	7	58.09	$1463\frac{1}{2}$	1	14	17.66	
Blue	$43\frac{1}{5}$	2	13 4	$153\frac{9}{10}$	7	48.65	$512\frac{2}{3}$		26	1.58	
Violet	$47\frac{4}{5}$	2	25.5	$73\frac{2}{5}$	3	42.9	$332\frac{1}{3}$		16	52.28	
Grey I	$36\frac{1}{5}$	1	49.9	$58\frac{4}{5}$	2	59.1	$128\frac{1}{2}$		6	31.5	
Grey II	$35\frac{3}{5}$	1	48.4	$107\frac{4}{5}$	5	28.46	$1499\frac{3}{5}$	1	16	7.6	

Table XII.—On Green Ground.

Observer: Mr. Lane.

Colour.	I. Achromatic threshold.			II. Chromatic threshold.			III. Characteristic colour threshold.				Remarks
	Diagonal of diaphragm opening in 1000ths of an inch.	Visual angle of diagonal of diaphragm opening.		Diagonal of diaphragm opening in 1000ths of an inch.	Visual angle of diagonal of diaphragm opening.		Diagonal of diaphragm opening in 1000ths of an inch.	Visual angle of diagonal of diaphragm opening.			
		′	″		′	″		°	′	″	
Purple	127⅓	6	27.8	132⅓	6	43.6	389		19	42.92	
Red	82	4	9.75	93⅓	4	44.1	153		7	46.	
Orange	90	4	34.1	148⅔	7	32.8	382⅓		17	40 84	Red at full.
Yellow I	100⅓	5	55.5	121	6	0.	457		23	12.06	
Yellow II	120⅓	6	6.55	187⅓	9	31.	309		15	41.24	
Yellow-green	152⅓	7	43.95	291⅓	14	47.4	1670	1	21	46.6	
Blue-green	210⅓	10	40.6	300	15	0.	1805	1	31	37.8	
Blue	141⅓	7	9.5	269	13	39.4	269		13	39.4	
Violet	129	6	33.	148⅔	7	52.8	159		8	4.3	
Grey I	59⅔	3	1.7	165⅔	8	24.55	....	....			
Grey II	187⅔	9	31.6	222	11	16.2	....	....			

Table XIII.—On Green Ground.

Observer: Dr. Kirschmann.

Colour.	I. Achromatic threshold.			II. Chromatic threshold.			III. Characteristic colour threshold.				Remarks.
	Diagonal of diaphragm opening in 1000ths of an inch.	Visual angle of diagonal of diaphragm opening.		Diagonal of diaphragm opening in 1000ths of an inch.	Visual angle of diagonal of diaphragm opening.		Diagonal of diaphragm opening in 1000ths of an inch.	Visual angle of diagonal of diaphragm opening.			
		′	″		′	″		°	′	″	
Purple	67	3	24.1	88	4	28.	628		31	42.9	Seen as reddish-purple at full.
Red	81½	4	8.24	81½	4	8.24	160		8	7.37	
Orange	80½	4	5.2	89½	4	32.6	160½		8	8.9	Seen red at full.
Yellow I	74	3	45.37	81¼	4	7.5	1860	1	34	23.36	Red-orange at full.
Yellow II	103¼	5	14.6	103¼	5	14.6	789½		40	4.8	
Yellow-green	127½	6	28.39	215	10	54.9	1027		52	8.26	
Blue-green	104	5	16.79	124	6	17.75	979½		49	43.5	
Blue	78½	3	59.	125	6	20.79	461½		23	25.72	
Violet	74½	3	46.9	99	5	1.5	362½		18	24.16	
Grey I	65	3	18	65	3	18.	1460	1	14	7.	Orange-yellow at full.
Grey II	79	4	0.5	125¼	6	21.5	1890	1	35	56.62	Yellowish-grey at full.

Table XIV.—On Green Ground.

Observer: Mr. Shaw.

Colour.	I. Achromatic threshold.			II. Chromatic threshold.			III. Characteristic colour threshold.				Remarks.
	Diagonal of the diaphragm opening in thousandths of an inch.	Visual angle of the diagonal of the diaphragm opening.		Diagonal of the diaphragm opening in thousandths of an inch.	Visual angle of the diagonal of the diaphragm opening.		Diagonal of the diaphragm opening in thousandths of an inch.	Visual angle of the diagonal of the diaphragm opening.			
		′	″		′	″		°	′	″	
Purple	81⅔	4	8 73	112⅔	5	43.2	255⅔		12	58.73	
Red	69½	3	31.67	85	4	18 86	130⅓		6	37.	
Orange	79	4	0.53	94⅓	4	47.15	1385	1	10	19.6	
Yellow I	82	4	9.75	90	4	34.1	332		16	51.3	
Yellow II	90	4	34.1	107½	5	27.5	787		39	59.2	
Yellow-green	321	10	16.8	349⅔	17	45.	1339⅝	1	7	10.2	
Blue-green	205	10	24 44	260	13	11.9	1147½		58	15.2	
Blue	87⅓	4	26.5	228	11	34.5	303		15	22.92	
Violet	85⅓	4	19.85	108⅓	5	30.05	574⅓		29	9.4	
Grey I	54	2	44.46	174	8	49.9	656		33	18.98	
Grey II	133	6	45.1	256½	13	1.25	990		50	14.6	

Table X V.—On Green Ground

Observer: Mr. Dodds.

Colour.	I. Achromatic threshold.			II. Chromatic threshold.			III. Characteristic colour threshold.			Remarks.
	Diagonal of the diaphragm opening in thousandths of an inch.	Visual angle of the diagonal of the diaphragm opening.		Diagonal of the diaphragm opening in thousandths of an inch.	Visual angle of the diagonal of the diaphragm opening.		Diagonal of the diaphragm opening in thousandths of an inch.	Visual angle of the diagonal of the diaphragm opening.		
		′	″		′	″		′	″	
Purple	$52\frac{3}{8}$	2	39.5	78	3	57.5	$95\frac{1}{8}$	4	49.66	
Red	$28\frac{1}{8}$	1	25.6	$58\frac{3}{8}$	2	57.	95	4	49.2	
Orange	$63\frac{1}{8}$	3	12.3	$73\frac{3}{8}$	3	43 5	$478\frac{1}{8}$	24	16.36	
Yellow I	60	3	2.7	74	3	45.35	$102\frac{1}{6}$	3	11.2	Seen as orange at full opening.
Yellow II	$54\frac{5}{8}$	2	46.4	$74\frac{9}{10}$	3	48.1	$131\frac{3}{5}$	6	40.2	
Yellow-green	$156\frac{4}{5}$	7	57.53	$198\frac{1}{5}$	10	3.3	895	45	26.72	
Blue-green	91	4	37.1	$113\frac{3}{4}$	5	46.45	$354\frac{1}{2}$	17	59.8	
Blue	$53\frac{3}{4}$	2	43.7	$90\frac{1}{8}$	4	35.6	$195\frac{1}{4}$	9	54.65	
Violet	$75\frac{1}{4}$	3	49.1	$84\frac{5}{8}$	4	17.73	319	16	11.9	
Grey I	$42\frac{1}{4}$	2	8.66	$58\frac{1}{4}$	2	57.4	....	....		
Grey II	$70\frac{3}{4}$	3	35.46	118	5	59.4	....	....		

REPRESENTATION OF THE SPACE-THRESHOLDS FOR GREEN GROUND.

Scale : ¾ of an inch=20 minutes.

Curve	III—Characteristic	Colour	Threshold	for Obs.	Dodds (Table XV).
"	IV—	"	"	"	Kirschmann (Table XIII).
"	V—	"	"	"	Shaw (Table XIV).
"	VI—	"	"	"	Lane (Table XII).
"	VII—	"	"	"	Creighton (Table XI).

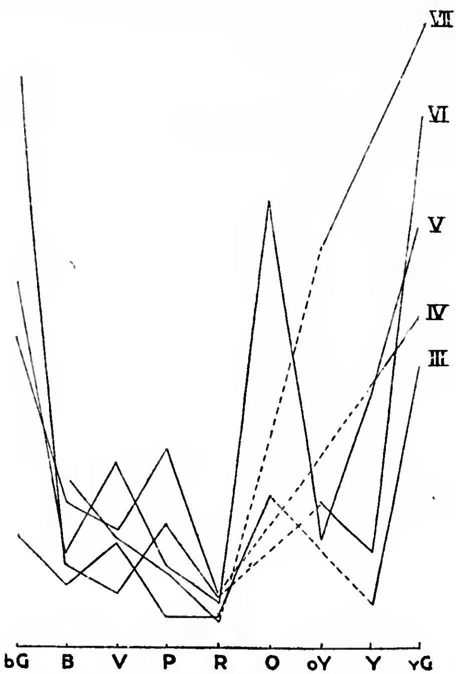

FIG. 10 (Tables XI to XV).

Table XVI.—On Blue Ground.

Observer: Mr. Robinson.

Colour.	I. Achromatic threshold.		II. Chromatic threshold.		III. Characteristic colour threshold.		Remarks.
	Diagonal of diaphragm opening in 1000ths of an inch.	Visual angle of diagonal of diaphragm opening.	Diagonal of diaphragm opening in 1000ths of an inch.	Visual angle of diagonal of diaphragm opening.	Diagonal of diaphragm opening in 1000ths of an inch.	Visual angle of diagonal of diaphragm opening.	
		′ ″		′ ″		° ′ ″	
Purple......	75 1/6	3 48.94	128 1/2	6 31.52	368 5/6	18 43.46	Seen first coloured red.
Red........	59 1/6	3 0.22	81 1/8	4 7.	81 1/8	4 7.	" "
Orange.....	74 1/5	3 16.5	116 1/3	5 54.34	....	....	" " and red at full open- [ing
Yellow I....	55 1/3	2 48.54	92 2/3	4 42.26	(2041 2/3)	(1 43 38.6)	Seen first coloured red; orange at full.
Yellow II...	57 7/12	2 55.4	156 11/12	7 57.96	(1635)	(1 23 0.)	" " chamois at full.
Yellow green	65	3 18.	256 1/5	13 0.33	1294 4/5	1 6 44.	
Green......	88	4 28.	367	18 43.	(1619 2/3)	(1 22 13.28)	
Blue-green..	86 5/6	4 24.48	271 11/12	13 48.26	(2066 1/3)	(1 44 53.58)	Seen at full plain green.
Violet......	82 5/6	4 49.33	134 5/12	6 49.5	830 1/2	42 3.88	
Grey I......	49 1/12	2 29.51	145 1/12	7 21.92	(2140 3/5)	(1 48 39.74)	Seen first coloured red; at full a grey yellow.
Grey II.....	74 1/6	3 45.91	213 1/2	10 50.32	....	....	Seen first coloured red.

Table XVII.—On Blue Ground.

Observer: Mr. Dodds.

Colour.	I. Achromatic threshold.		II. Chromatic threshold.		III. Characteristic colour threshold.		Remarks.
	Diagonal of diaphragm opening in 1000ths of an inch.	Visual angle of the diagonal of diaphragm opening.	Diagonal of diaphragm opening in 1000ths of an inch.	Visual angle of diagonal of diaphragm opening.	Diagonal of diaphragm opening in 1000ths of an inch.	Visual angle of diagonal of diaphragm opening.	
		′ ″		′ ″		° ′ ″	
Purple......	54½	2 46.	64½	3 16.5	104¾	5 19.	Seen first coloured red.
Red........	47⅔	2 25.	61	3 5.8	66½	3 22.5	" "
Orange.....	65⅔	3 20.	89⅓	4 32.	(960⅔)	(48 46.)	" " and red at full opening.
Yellow I....	67⅔	3 26.2	101⅓	5 8.66	1649	1 23 42.6	" " and orange-red at full.
Yellow II...	53⅓	2 42.4	88⅓	4 29.	535	27 9.2	" "
Yellow-green	73⅚	3 44.9	167¾	8 30.9	498¼	25 19.66	
Green......	102	5 10.68	173⅓	8 48.4	548¼	27 50.	
Blue-green..	108⅚	5 31.5	194⅚	9 53.4	826½	41 57.4	
Violet......	82⅚	4 2.3	91⅙	4 37.6	(105⅙)	(5 20.3)	Seen first coloured red; at full purple.
Grey I......	40	2 1.8	90	4 34.1	....	....	" "
Grey II.....	75⅔	3 50.16	158	8 1.2	....	....	

Table XVIII.– On Blue Ground.

Observer: Dr. Kirschmann (Right Eye.)

Colour.	I. Achromatic threshold.			II. Chromatic threshold.			III. Characteristic colour threshold.			Remarks.
	Diagonal of diaphragm opening in 1000ths of an inch.	Visual angle of diameter of diaphragm opening.	Visual angle of diagonal of diaphragm opening.	Diagonal of diaphragm opening in 1000ths of an inch.	Visual angle of diameter of diaphragm opening.	Visual angle of diagonal of diaphragm opening.	Diagonal of diaphragm opening in 1000ths of an inch.	Visual angle of diameter of diaphragm opening.	Visual angle of diagonal of diaphragm opening.	
		′ ″	′ ″		′ ″	′ ″		′ ″	° ′ ″	
Purple......	100½	3 36.46	5 6 12	146	5 14.46	7 24.72	397¾	14 16.68	20 11.54	Seen first coloured red.
Red........	71¾	2 34.54	3 38.55	84½	3 2.	4 17.38	134½	4 49.69	6 49.68	" "
Orange.....	85¼	3 3.6	4 19.66	105	3 46.14	5 19.8	229¾	8 14.8	11 39.82	Seen at full open'g as red.
Yellow I....	68	2 26.46	3 27.12	100	3 35.4	5 4.62	1241¾	44 39.98	1 3 9.8	Seen first coloured red.
Yellow II...	100½	3 36.46	5 6.12	126½	4 32.46	6 25.32	1119	40 10.14	56 48.4	
Yellow-green	122½	4 23.84	6 13.13	210½	7 33.38	10 41.18	801	28 45.22	40 39.82	Seen first coloured red.
Green......	124¾	4 28.68	6 20.	205	7 21.54	10 24.44	570½	20 28.76	28 57.74	" " "
Blue green .	187¼	6 43.30	9 30.36	272¼	9 46.38	13 49.27	1944¼	55 26.28	1 18 23.96	" " brown.
Violet......	101¾	3 39.14	5 9.92	131¼	4 42.68	6 39.8	1635¾	58 43.04	1 23 2.26	" " red.
Grey I......	106¼	3 48.84	5 23.64	92¼	3 18.69	4 40.89	(1588½)	(57 1.38)	(1 20 38.36)	Seen orange-yellow at full.
Grey II.....	128½	4 36.77	6 31.41	190¼	6 49.76	9 39.50	877	31 28.91	44 31.31	Seen dirty yellow at full.

Table XIX.—On Blue Ground.

Observer: Dr. Kirschmann (Left Eye).

Colour.	I. Achromatic threshold. Diagonal of diaphragm opening in 1000ths of an inch.	I. Achromatic threshold. Visual angle of diagonal of diaphragm opening.	II. Chromatic threshold. Diagonal of diaphragm opening in 1000ths of an inch.	II. Chromatic threshold. Visual angle of diagonal of diaphragm opening.	III. Characteristic colour threshold. Diagonal of the diaphragm opening in 1000ths of an inch.	III. Characteristic colour threshold. Visual angle of diagonal of diaphragm opening.	Remarks.
		′ ″		′ ″		° ′ ″	
Purple	99	5 1.5	139	7 3.4	462	23 27.2	Seen first coloured red.
Red	56	2 50 55	95	4 49.2	95	4 49.2	
Orange	78	3 57.5	136	6 54.3	2250	1 54 13.	Seen first coloured red and remains red to [the end.
Yellow I	70	3 33.2	101	5 7.6	1098	55 40.7	Seen first coloured red.
Yellow II...	90	4 34.1	160	8 7.33	1400	1 11 4.36	" " "
Yellow-green	138	7 0.4	205	10 24.45	1139	57 49.4	" " brown.
Green	125	6 29.9	190	9 38.66	1970	1 40 0.36	" " reddish brown.
Blue-green ..	289	14 40.32	305	15 29.04	822	41 43.84	
Violet	100	5 4.55	170	8 37.8	....	....	At full opening only violet purple.
Grey I......	65	3 18.	117	5 56.3	1682	1 25 23.33	
Grey II	82	4 9.75	222	11 16.2	1098	55 44.52	

Table XX.—On Blue Ground.

Mixed Observers (8).

Colour.	I. Achromatic threshold. Diagonal of the diaphragm opening in 1000ths of an inch.	I. Visual angle of the diagonal of diaphragm opening.	II. Chromatic threshold. Diagonal of the diaphragm opening in 1000ths of an inch.	II. Visual angle of the diagonal of diaphragm opening.	III. Characteristic colour threshold. Diagonal of diaphragm opening in 1000ths of an inch.	III. Visual angle of the diagonal of diaphragm opening.	Remarks.
		′ ″		′ ″		° ′ ″	
Purple......	$74\frac{1}{2}$	3 46.9	$101\frac{1}{2}$	5 9.2	$660\frac{1}{4}$	33 31.11	Seen first coloured red.
Red	$54\frac{5}{8}$	2 46.01	$67\frac{2}{5}$	3 26.21	$121\frac{7}{8}$	6 11.23	" " "
Orange	55	2 47.49	$96\frac{1}{8}$	4 52.8	$607\frac{5}{14}$	30 50.	" " "
Yellow I....	$51\frac{3}{8}$	2 36.49	$67\frac{1}{4}$	3 24.51	1514	1 16 51.46	" " "
Yellow II ..	$70\frac{13}{18}$	3 [illegible]5.42	$122\frac{1}{4}$	6 12.	$1159\frac{6}{7}$	58 39.77	" " "
Yellow-green	$60\frac{3}{7}$	3 31.48	$236\frac{1}{5}$	11 59.4	$1110\frac{1}{3}$	56 23.	
Green	$114\frac{9}{14}$	4 43.93	$239\frac{5}{14}$	12 9.11	$1250\frac{1}{3}$	1 3 29.42	Seen first coloured green o[r] blue.
Blue-green ..	$99\frac{7}{8}$	5 4.22	$316\frac{3}{8}$	16 3.67	$1933\frac{1}{3}$	1 38 9.81	
Violet	$71\frac{1}{6}$	3 36.7	112	5 41.15	$1010\frac{1}{4}$	51 18.6	Seen first coloured red.
Grey I......	$42\frac{1}{2}$	2 9.45	92	4 40.23	$1100\frac{1}{10}$	55 50.84	" " "
Grey II	83	4 12.82	212	10 45.75	....	....	

REPRESENTATION OF THE SPACE-THRESHOLDS FOR BLUE GROUND.

Scale : ⅜ of an inch=20 minutes.

Curve I—Achromatic Threshold (average of 8 observers).
" II—Chromatic " "
" III—Characteristic C. Thr. for Obs. Dodds (Table XVII).
" IV— " " " Kirschmann, left eye (Table XIX).
" V— " " " " right eye (Table XVIII).
" VI— " " 8 observers, averaged (Table XX).

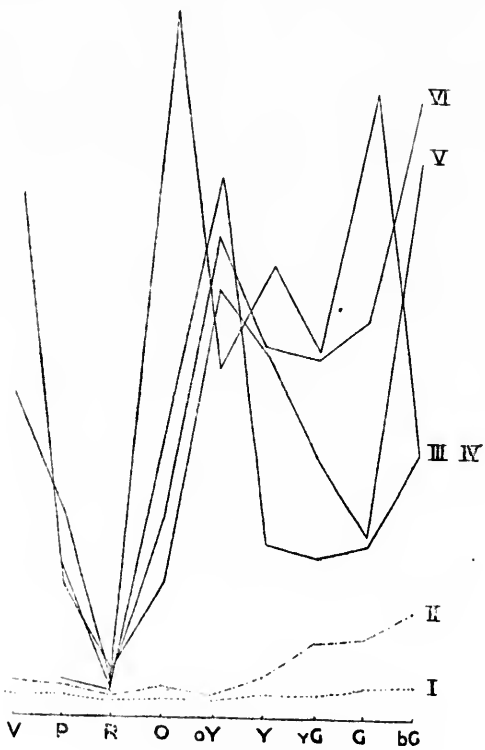

FIG. 11 (Tables XVI to XX).

SUMMARY.

I.—Black Ground.

1. The chromatic space-threshold has two decided maxima, in the yellow and in the blue regions.

2. The characteristic colour threshold has three strongly marked maxima, at orange, yellow-green and violet; and three decided minima, in the yellow, blue-green and red-purple regions.

3. For red the achromatic, chromatic and characteristic thresholds coincide; and for yellow the chromatic and characteristic thresholds coincide.

II.—Grey Ground.

1. Similar results to those noted for black ground are obtained for the maxima and minima, except that the second minimal region includes yellow no. 1 (orange-yellow), and that the second maximal region includes green. We may also notice that the maxima are considerably raised while the minima retain in general their former position.

III.—Coloured Grounds.

A very peculiar change of the antagonistic colour relations seems to take place. In small areas it is not the complementary colour which finds its most favourable conditions for being recognized on coloured grounds. On a red ground the minimum of the characteristic colour threshold is decidedly in the blue; and on a blue ground the curve has an exceedingly marked minimum in the red. Thus for small surfaces on coloured grounds blue and red act as complementaries.

A CASE OF ABNORMAL COLOUR-SENSE EXAMINED WITH SPECIAL REFERENCE TO THE SPACE-THRESHOLD OF COLOURS

By

J. W. BAIRD, B.A., and R. J. RICHARDSON, B.A.

A CASE OF ABNORMAL COLOUR SENSE, EXAMINED WITH SPECIAL REFERENCE TO THE SPACE THRESHOLD OF COLOUR.

BY J. W. BAIRD, B.A. AND R. J. RICHARDSON, B.A.

Notwithstanding the extensive literature already before the world upon the subject of colour-blindness, we hope that an account of our examination of the case about to be described may be of interest. The classification of the human family into colour-blind and non-colour-blind is at best a matter of rough and somewhat arbitrary judgment. The colour sense is called normal when expressions and actions lead us to suppose that the relations of the colour sensations are the same as with the majority of people, while persons whose expressions and actions show us that these relations differ considerably from those of the majority are called colour-blind, or persons of abnormal colour-sense.*

Colour-blind persons may, according to Dr. Kirschmann, be classified on the basis of the degree of their abnormality into (1) achromates—who are totally devoid of colour-sense and see objects only in various degrees of grey, (2) dichromates—who see only two antagonistic colour qualities, such as red and green or blue and yellow, and (3) abnormal polychromates—who distinguish more than two colours, though the relations of their colour-sensations differ from those of the normal.

The results of the investigations of colour-blindness can only approximate to accuracy, owing chiefly to the difficulties which we always encounter when we attempt to ascertain and describe the psychic states of others. Colour-blind individuals use the ordinary colour vocabulary, which is quite inadequate to express their sensations of colour.

The experiments which furnished the data for this paper were conducted in the psychological laboratory of the University of Toronto at the request of Dr. Kirschmann, director of the laboratory, to whom our thanks are due for co-operation and suggestions.

*This is the definition of normal colour sense and colour-blindness which Dr. Kirschmann gives in his lectures on Psychological Optics.

We are also indebted to Mr. W. B. Lane, M.A., now Fellow in Psychology in the University of Wisconsin, to Mr. F. S. Wrinch, M.A. and Mr. A. H. Abbott, B.A., Assistant in the psychological laboratory, for valuable assistance in our work.

This case of colour-blindness was investigated in the following ways:

I. Spectroscopic examination.

II. Stilling's Pseudo-isochromatic tables.

III. Colour equations.

IV. Experiments on space-threshold of colours under contrast influence.

I. A series of observations was made upon the solar spectrum by observer R. (whose colour-sense is abnormal), with a view to determining the nature of his deviation from the normal. The wave-lengths are calculated by graphical interpolation, the numbers for the principal lines being taken from the tables of Rowland. Mr. R. always claims that he sees three distinct colours, red, green and blue, in the spectrum.

Using the left eye Mr. R. saw the light,

920 $\mu\mu$ to 670 $\mu\mu$, dark brownish red
670 $\mu\mu$ to 540 $\mu\mu$, uniform red
(590 $\mu\mu$, red of deepest saturation)
540 $\mu\mu$ to 493 $\mu\mu$, green
(513 $\mu\mu$, best green)
493 $\mu\mu$ to 384 $\mu\mu$, blue
(429 $\mu\mu$, deepest blue).

The maximum of light intensity was seen at 590 $\mu\mu$. At 762 $\mu\mu$. the line A was seen as distinctly as the other lines, whilst observers B and K could see it, but with difficulty. In the red end of the spectrum in addition to the lines A, B, and C, other lines were clearly distinguishable at points corresponding to the following wave-lengths: 603 $\mu\mu$, 626 $\mu\mu$, 644 $\mu\mu$, 728 $\mu\mu$, *and at two points beyond the A line in the ultra-red spectrum.* The wave-lengths corresponding to the latter points are not computable from any data within our reach, but we estimate them from our interpolation-curve to be the Z line and the X_4 line (Abney), corresponding to which are the wave-lengths 822 $\mu\mu$ and 880 $\mu\mu$ respectively.

For the right eye the colours and their positions were given as follows:—

900 $\mu\mu$ to 687 $\mu\mu$, dark brownish red
(726 $\mu\mu$, most characteristic brown-red
687 $\mu\mu$ to 541 $\mu\mu$, red
(590 $\mu\mu$, red of deepest saturation)

541 $\mu\mu$ to 501 $\mu\mu$, green
(527 $\mu\mu$, best green)
501 $\mu\mu$ to 384 $\mu\mu$, blue
(427 $\mu\mu$, blue of deepest saturation).

The lines in the ultra-red spectrum (especially that at 822 $\mu\mu$) were seen as distinctly as with the left eye, whilst observers B and K could see absolutely nothing beyond 762 $\mu\mu$ and 770 $\mu\mu$ respectively.

In addition to the examination of the solar spectrum with the spectroscope, observations were made upon an inverted spectrum* projected on a screen by means of an arrangement recently devised by Dr. Kirschmann for the purpose of comparing the ordinary and the inverted spectrum. One of these spectra had its colours arranged in the usual order—purple being absent. The other was thrown upon the screen parallel with and contiguous to the first, but with the order of the colours inverted; that is, the colours proceeded through yellow, orange, red, purple and violet to blue—green being absent. A photograph of the two spectra is given (p 101.)

The only difference noted by observer R. in these spectra was that in the inverted form the dark brownish red was missing. *He could distinguish no difference in colour tone in the central section of the two spectra,* that is, between the purple of the inverted and the green of the ordinary spectrum. The statements of observer R. were essentially the same when the two spectra were divided by means of interference bands.

II.—A series of tests for colour-blindness by means of Stilling's Pseudo-Isochromatic Tables (third edition, 1889) yielded the following results:

Plate I (orange-red figures on brown ground) was read slowly and with a great deal of uncertainty. The ground was called green, the darker patches brown or purplish. The figures were called blood-red, their lighter patches yellowish. The figures were more easily distinguished through a red glass, but best of all through blue.

Plate II (orange-red figures on brown ground) was more easily read than Plate I, but also with considerable uncertainty. The ground was called green, the darker patches murky red like the extreme red end of the spectrum. The figures were said to be com-

*For description of the inverted spectrum see the article by Dr. Kirschmann on Colour Saturation in the American Journal of Psychology, Vol. vii., p. 387, and note at the end of these articles.

posed of patches of red and orange-red. Green glass was of no help in reading the figures, but violet glass was of great assistance.

Plate III (orange figures on brown ground) was read with much hesitation. The figures were thought to be a poorly saturated red and the ground to be of patches of light and dark green. It was easily read with a blue glass.

Plate IV (red figures on coffee-brown ground) was more easily read than plates I, II or III. The figures were seen as bright blood-red, the ground in two saturations of purple. It was less easily read through blue and green glasses, more easily through red glass.

In plate V (wine-red figures on dark chocolate ground) the figures could be seen. The colours of the plate seemed to be two saturations of purple, the darker patches like clotted blood, the lighter like "purple-green." Through a red glass the figures could be read, though with much hesitation.

Plate VI (green figures on brown ground) was read very slowly, and only after a deliberate examination. It could not be read through blue glass; yellow-green glass improved it, though it was not yet distinct. Through red glass it was quite distinct and easily read. The ground was said to be bright reddish purple, the figures purplish red.

Plate VII (cherry-coloured figures on greyish ground) was fairly well read. The ground had lighter patches of poorly saturated purple or well saturated green, and darker patches of dark brown or dark purple. The figures were quite distinct through a red glass. Blue and green glasses were of no help. The purple glass was an improvement but not so much so as the red.

Plate VIII (red figures on orange ground) was more easily read than any of the above. The figures were "purplish green," the ground composed of patches of blood-red and poorly saturated red. Red, green, blue and purple glasses were of no assistance.

Plate IX (lilac figures on grey-green ground) was read very slowly, one figure at a time. The figures were blue-green, the ground green and brown-green or purple. None of the glasses were of any assistance.

Plate X (red figures on light brown ground) was the most distinct of all. The figures were a very well saturated red, the ground a poorly saturated green with a less saturated red than the figures. Red glass altogether prevented the possibility of reading it, green and blue glasses made no difference in the ease with which it could be read.

III.—Colour equations by means of rotating discs were also made, of which we give the following examples:

I. 286° green + 74° blue = 130° white + 230° black.

II. 68° blue + 292° red = 42° white + 380° black.

In the first of these cases the whole disc was seen as grey, and in the second it was described as purple.

IV.—For a description of the apparatus used in the contrast experiments the reader is referred to the paper by Mr. W. B. Lane. The apparatus was arranged in such a way that it was possible to measure with great accuracy the magnitude which is necessary for a coloured surface, in order to be seen (*a*) as light, (*b*) as colour, (*c*) in its proper colour. The experiments can be performed for a black or any uncoloured ground as well as under the influence of pure colour contrast, *i.e.* for coloured grounds under approximately complete exclusion of intensity contrast and saturation contrast.

In the following tables which are compiled from records of experiments made by means of this apparatus, we shall compare the abnormal colour sense of observer R. with the normal, by a statement of the visual angles which represent their achromatic and chromatic thresholds. By achromatic threshold we understand the smallest visual angle at which the coloured surface concerned could be seen as something different from the ground; by chromatic threshold, the smallest visual angle at which the colour of the surface was identified.

The inducing surface for Table I was grey, into the centre of which were introduced in turn the ten different colours which were at our disposal. The colours were almost pure spectral colours; their spectroscopic analysis also will be found in the foregoing paper by Mr. Lane, who used for the purpose of his research the same apparatus.

Table I.—INDUCING SURFACE GREY.

Induced colour.	Size of visual angle at which the induced colour was seen as something different from the ground.		Size of visual angle when the induced colour was identified.	
	By normal colour sense.	By abnormal colour sense.	By normal colour sense.	By abnormal colour sense.
	′ ″	′ ″	′ ″	
Red	2 56.6	3 45.4	6 36.7	*Not identified.
Orange	3 33.2	5 50.2	4 55.5	"
Orange-yellow	4 3.7	6 14.7	9 43.7	"
Yellow.......	3 35.45	4 34.1	4 47.67	18′ 59.2″
Yellow-green .	3 39.3	5 14.7	15 16.8	32′ 43.32″
Green	3 43.2	7 33.9	16 25.4	Not identified.
Blue-green ..	3 33.2	7 27.7	8 9.85	"
Blue	4 25.9	7 39.1	6 50.4	9 58″
Violet	4 12.8	7 4	23 36.4	15′ 9 6″
Purple	4 17.4	4 46.2	8 23.55	1° 7′ 6.6″

*The full opening of the induced surface subtended a visual angle of 2° 6′ 38.92″, beyond which magnitude the experiment could not be extended, and below it the observer was unable to identify the induced colour in its own quality. These cases are indicated in our tables by "not identified."

Table II.—INDUCING COLOUR RED.

Induced colour.	Size of visual angle at which the induced colour was seen as something different from the ground.		Size of visual angle when the induced colour was identified.	
	By normal colour sense.	By abnormal colour sense.	By normal colour sense.	By abnormal colour sense.
	′ ″	′ ″	° ′ ″	
Orange	3 16.05	7 35.4	1 4 30.06	Not identified.
Orange-yellow	3 29.92	7 54.1	1 14 35.02	"
Yellow	4 27.3	7 4	Not identified.	1° 17′ 40.8″
Yellow-green .	3 8.02	6 12.2	1 21 34.6	54′ 39.4″
Green	2 58.5	5 47.3	41 27.4	Not identified.
Blue-green ...	2 58.74	5 48	46 7.11	11′ 48 2″
Blue	2 56.36	6 1	26 26.4	15′ 9.26″
Violet	2 48.5	5 56.3	51 16.55	Not identified.
Purple	3 57.48	6 16.2	52 8.86	37′ 38″

Table III.—Inducing Colour Green.

Average of five trials.

Induced colour.	Size of visual angle at which the induced colour was seen as something different from the ground.		Size of visual angle when the induced colour was identified.	
	By normal colour sense.	By abnormal colour sense.	By normal colour sense.	By abnormal colour sense.
	′ ″	′ ″		° ′ ″
Red	3 24.1	6 11.6	4′ 43.2″	1 25 18.3
Orange	4 37.1	9 38.6	Not identified.	1 15 41.6
Yellow	6 5.6	6 30	15′ 41.2″	Not identified.
Yellow-green .	6 17.7	8 7.5	Not identified.	15 1.8
Blue-green ...	9 11.3	6 23.8	19′ 15.98″	21 38.4
Blue	5 7.6	8 4.3	13′ 33.4″	15 5.8
Violet	6 36	2 52.9	10′ 48.8″	35 26.8
Purple.......	6 30	11 11	19′ 45″	1 8 1.5

Table IV.—Inducing Colour Blue.

Average of three trials.

Induced colour.	Size of visual angle when induced colour was seen as something different from the ground.		Size of visual angle when induced colour was identified.	
	By normal colour sense.	By abnormal colour sense.	By normal colour sense.	By abnormal colour sense.
	′ ″	′ ″	° ′ ″	′ ″
Red	3 38.55	4 28	6 49.68	52 48.8
Orange	4 19.66	4 58.5	11 39.82	Not identified.
Yellow	5 6.12	3 39.3	56 48.4	"
Yellow-green .	6 13.13	9 5.2	40 39.82	"
Green	6 20	15 26.3	28 57.74	"
Blue-green ...	9 30.36	7 33.8	1 18 23.96	"
Violet	5 9.92	7 6.4	1 23 2.26	"
Purple	5 6.12	10 58	20 11.54	"

SUMMARY.

1. In the case of abnormal colour-sense, which we have examined, the colour spectrum is not only not shortened, but it is actually *considerably lengthened* at the red end. The violet end is seen as by the normal eye.

2. Only three qualities were distinguished in the spectrum—red, green, and blue,—and it remains uncertain whether green was identical with grey or not.

3. The differences in the blue part of the spectrum were claimed to be but differences of saturation.

4. The only difference detected between the ordinary and the inverted spectrum was that the deepest red was missing from the inverted spectrum; otherwise the two were identical—*i.e.*, the ordinary spectrum contained the same colours as the inverted and in the same order, except red. Nothing was missing from the ordinary spectrum which was found in the inverted spectrum. A point in the inverted spectrum—purple—was judged to be exactly like the green of the ordinary spectrum which stood below it.

5. As to the experiments on the space threshold:

a. In the case of the grey background [non-contrast] the variations of the achromatic threshold for the normal and abnormal were fairly parallel for purple, red, orange, and yellow; but the threshold for the colour-blind observer was considerably higher throughout.

b. A similar correspondence was noticeable in the chromatic threshold on red ground.

(In both of the above the achromatic threshold was invariably higher to the abnormal than to the normal colour sense.)

c. When green was the inducing colour the achromatic threshold for the abnormal colour-sense was considerably lower than that for the normal in the cases of blue-green, and violet, though higher for all other colours.

d. In the blue contrast the normal threshold gradually increased from red to blue-green and decreased from violet to red while the abnormal had its maximum points in green and purple, and its minimum in yellow.

e. With regard to the chromatic [characteristic colour] threshold, the fact that only the yellow and blue, and sometimes the neighbouring tones were identified seems to prove clearly the dichromatic character of this case of colour-blindness.

6. The influence of border contrast was distinctly noticeable in the abnormal colour-sense, usually appearing when the visual angle reached a magnitude of about 1° 4′, and persisting to the full opening.

7. The effect of contrast was usually much greater in the abnormal sense than in the normal for those colours which were at the disposal of the colour-blind observer.

The accompanying diagram gives a graphical representation of the achromatic threshold for the normal and the colour-blind eye.

Fig. 1.

Fig. 2.

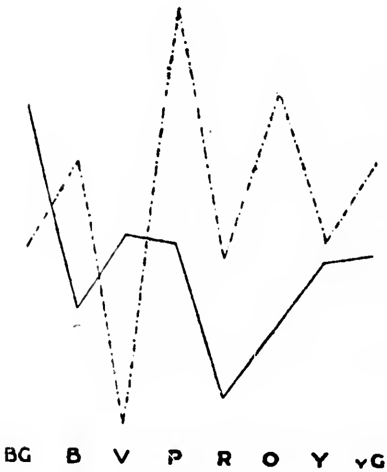

Fig. 3.

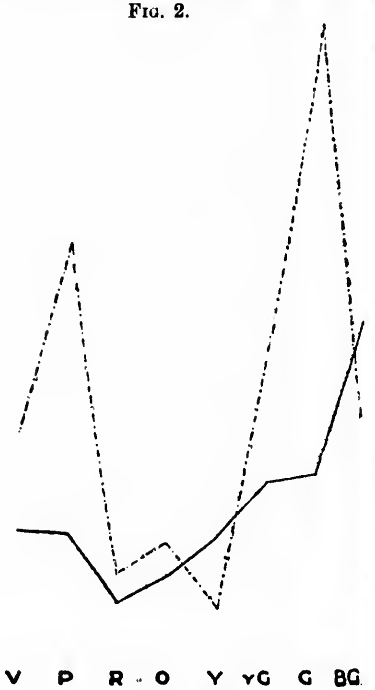

Fig. 4.

Achromatic Threshold for Normal Colour-Sense and Colour-Blind.

Fig. 1. Grey Ground (Table I).
" 3. Green " (Table III).

Fig. 2. Red Ground (Table II).
" 4. Blue " (Table IV).

Curve ——— = Normal Colour-Sense.
" - - - - - - = Colour-Blind.

ADDITIONAL REMARKS ON COLOUR BLINDNESS.

BY A. KIRSCHMANN.

The case of colour-blindness above reported deserves attention in several respects. Its most particular feature is the fact that in this case of abnormal colour-sense we have to deal *with an enlarged spectrum.* A considerable part of the ultra-red spectrum, which is invisible for the normal eye, is seen and lines in it are distinguished. I have always laid emphasis upon the fact that the length of the spectrum and the manifoldness of colour-sensations do not stand in any direct connection. There are cases in which the spectrum is shortened and the colour-sense is quite normal; there are others of partial or total colour-blindness in which the spectrum has its ordinary extension on both sides. The case in question in the foregoing article *proves that pronounced colour-blindness may even be associated with a considerably lengthened spectrum.*

Further, the experiments with the inverted spectrum prove beyond any possible doubt:

1. That below about 540$\mu\mu$ no differences in colour quality are distinguished. Red, orange and yellow are seen as the same colour-tone. It must be pointed out that from the circumstance that all these colours are called *red,* it does not follow that the colour-blind sees them like our red.

2. All wave-lengths above about 500-490$\mu\mu$ are again seen as one quality (which is called blue), but in different saturations.

3. The colour missing in the ordinary spectrum, reddish purple, *is seen exactly of the same quality as that in the middle of the spectrum,* the green between E and F. Whether this part of the spectrum is seen identical with colourless light or not cannot be decided with certainty from the results of the observations. The fact that the colour-blind localizes the "best green," and that he decidedly denies that it could be called white or grey seem to contradict this; the blunders in the distinction of grey and green pigments, on the other hand, support the purely dichromatic character of this system of colour-sensations.

I may mention in this connection that so-called colour-equations are not an absolutely infallible means upon which to decide regarding dichromacy in cases similar to the one stated above. The assumption that everything which is colourless for the normal eye must appear so to the colour-blind also, is incorrect as soon as it is admitted that the relations of complementary qualities may be shifted in the case of an abnormal colour-sense.

The case above reported is different from all other cases which have come under my notice, and thus forms one proof more for the untenableness of those theories which try to force all cases into two classes, with little modifications—red-green blinds and blue-yellow blinds. On account of the enlarged spectrum, which had not been observed hitherto, this case may find its place at the side of others which give a good deal of trouble to the adherents of the component theories, that of Von Vintschgau,* and case five in my own paper.† (I have just learned that the latter, a very interesting case of monocular colour-blindness, has been investigated again by Hering, and I sincerely trust that this renowned physiologist will no longer hesitate to publish the results of his investigation, which adherents and opponents of the component theories are equally anxious to read.)

It is not seldom that colour-blinds ask whether their defect could be cured or not; or they ask for the prescription of glasses with which "they can see the colours." Without entering into any discussion of the question whether the colour-sense might be changed or not by means of drugs, hypnotism, etc., I may be permitted to state, that it is quite possible to furnish the colour-blind with some means by which roughly to avoid mistakes in the choice and designation of colours. This would be of great value to him, especially where his occupation involves a constant dealing with pigments or other colours. I have twice given "glasses" to colour-blinds. The principle itself is not new, for I think Delboeuf‡ used many years ago a solution of fuchsin for similar purposes. Red objects look bright when seen through this medium, whilst green surfaces appear dark. Thus a red-green blind may distinguish red and green, by judging of their brightness when seen through a medium which absorbs either all the red or all the green rays. The first of these two cases was a Mrs. A., a milliner in San Francisco She was a dichromate with the indifference-line near *B*. Her defective colour-sense did not seem to have any damaging influence on her business; it obviously caused more trouble to her own conscience than to the taste of her customers.

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*Pflügers Archiv, xlviii, p. 431 ff.

†Philosoph. Studien, viii p. 196 ff.

‡ I have not the literature at hand.

With respect to the question of the heredity of colour-blindness it may be worth while to mention that a sister of this lady was colour-blind also. Her brother was not colour-blind. Whether one of her parents was colour-blind or not could not be ascertained. Of the two children of Mrs. A., a daughter of thirteen years was not colour-blind, whilst the little son, ten years old, had the same defect in his colour-sense as his mother.

I gave to this lady two "glasses," *i.e.*, two combinations of plates of col ured glass and gelatine films, the composition and absorbing power of which, as approximately ascertained with the spectroscope, were as follows:

	Light transmitted with small opening of the slit.	with wide opening of the slit.
I. Composed of 1 red glass (copper-oxide), 1 film of yellow gelatine, 1 film of purple gelatine	700—590$\mu\mu$	750—570$\mu\mu$
II. Composed of several blue and green gelatine films	550—480 "	560—460 "

Combination I bore on its handle the direction: All objects which, viewed through this glass, lose much of their brightness, *cannot be red.* Combination II had the direction: All surfaces which lose much of their brightness, when looked at through this glass, *cannot be green.* Now, in order to become accustomed to the use of these instruments, and to use them with success in cases of lighter saturation-degrees of the colours, the colour-blind must practise with samples which form a kind of standard with which to compare the surfaces in question. For this purpose I gave the colour-blind two sets of samples, one on black, the other on white ground. Each of the two sets consisted of thirty-six little discs of coloured paper, about an inch in diameter. Ten of these discs represented the spectral colours in as good a saturation as pigment papers allow, ten the corresponding lighter tints, and ten others the darker shades of the same colours. Besides these there were three samples of grey and three of brown. The names of the colours were written (with gold bronze, in order to be visible through any glass) at the side of each disc.

If the colour-blind is uncertain whether to call a surface red, green, or grey, he will look at it through the glasses described and in more difficult cases of slighter tinges of these colours he will carefully compare the behaviour of their intensities under the influence of the absorbing media with that of the samples. It is comparatively easy to identify grey surfaces by means of this method, for they keep up about the same brightness for both absorbing glasses, whilst any red or green tinge reveals itself by contrary behaviour toward the two instruments. The distinction of very whitish colours, as light rose, lilac, etc., requires some practice, and a sharp and unprejudiced judgment.

The other colour-blind to whom I gave "glasses" of similar construction was Mr. S., a student at the School of Practical Science in Toronto. He is a pronounced dichromate, with an indifferent region extending a little on both sides of the line F. I made in this case three combinations, one for the red end of the spectrum to about $620\mu\mu$, one which absorbed everything except the green, and a third which absorbed the green and transmitted the rays of the two ends of the spectrum fully. As standard colours I gave in this case three sets, one on white, one on black, and one on grey ground. Each set contained twenty colours, each in three degrees of saturation. There was a special table arranged for grey and brown. The successful use of so complicated an arrangement requires of course on the part of the colour-blind intelligence, sharp observation, and perseverance.

The accompanying plate shows, as well as it can be reproduced by a half-tone cut, in its upper part (Fig. 1) a photograph of the spectra mentioned in the foregoing article. The limits of the visible spectra are indicated by perpendicular lines crossing the whole field. At the end of the shorter waves the photograph shows distinctly beyond the visible part the ultra-violet in the ordinary, and the ultra-yellow in the inverted spectrum. The two smaller photographs, Figs. 2 and 3, are obtained by means of light reflected from very thin films of mica. On account of the path-difference of the rays from the front and the back surface of the film they show interference-bands, which are equally visible in the ordinary as in the inverted spectrum.*

*As no description has yet been given of the apparatus by means of which the normal and inverted spectra are projected on the screen together, I may here give a brief account of it. I have always used an electric lantern as the source of light in this experiment, since it is more convenient than sunlight. With the exception of the plate to be next described, the rest of the apparatus consists of a large lens and a prism. The special part of the apparatus consists of a very thin plate of glass (I have used a microscope cover-glass) of any desired size, half of which is made opaque with the exception of a slit of the required width and length. The other half of the glass plate is left transparent with the exception of a portion, exactly opposite the end of the above mentioned slit, and about the same size, which is also made opaque. This opaque strip I have called a "negative slit." The plate is inserted in the path of the rays of light, which after passing it are focussed and deflected by the lens and prism respectively.

FIG. 1.

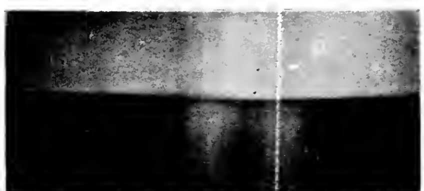
FIG. 2.


FIG. 3.