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A NEW METHOD OF HETEROCHROMATIC PHOTOMETRY

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In a former paper¹ it was stated that a satisfactory method of photometry should combine the following features. (1) It should enable us to detect small differences in luminosity and to reproduce our results for a given observer with a small mean variation and for a number of observers with a comparatively small mean variation. That is, the method should possess an adequate degree of sensitivity, and should give results with a satisfactory degree of reproducibility.² (2) It should be known either to possess of itself logical sureness of principle or its results must agree in the average with those of some method which can be shown to possess this sureness of principle. Methods having these features have been developed for the photometry of colorless light. The problem for the photometry of colored light, however, has presented great difficulty.

The methods for the photometry of colored light may be grouped under two headings: the direct and the indirect methods. In the former class we have the method of direct

¹ Ferree, C. E. and Rand, Gertrude, 'A Preliminary Study of the Deficiencies of the Method of Flicker for the Photometry of Lights of Different Color,' *Psychol. Rev.*, 1915, 22, pp. 110-162.

² It is scarcely needful to point out in this connection that the method should give results with a satisfactory degree of reproducibility for observations separated both by short and by long intervals of time.

comparison or as it is sometimes called the equality of brightness method. This method is generally accredited with sureness of principle but it is deficient on the side of sensitivity and reproducibility when lights differing in color value are compared.¹ Of the latter class the method of flicker has received the greatest amount of attention and has been the most favored. But in our former paper it was shown (1) that the method of flicker, so far as it has been developed up to the present time, does not possess of itself the sureness of principle needed to meet the requirements of a satisfactory method; and (2) that as yet its results have not been found to agree on the average with those of any method which can be shown to have this sureness of principle. It was also stated that in a later paper a method of photometry would be described which possesses approximately as high a degree of sensitivity and of reproducibility as the method of flicker and gives results which agree very closely on the average with those obtained by the equality of brightness method, much more closely than results obtained by the method of flicker. It will be the purpose of this paper to give a brief description of this method. It was first used by the writers in connection with work in color sensitivity for the purpose of detecting small changes on the illumination of a room by daylight.² Although not so convenient perhaps as the equality of brightness method for many of the purposes for which photometry may be used, for this work the method did not present any great amount of difficulty, and it proved to be much more sensitive than the equality of brightness method. The equality of brightness photometers of the Sharp-Millar type, for example, are very insensitive for the determination of the illumination of a room by daylight, because the standard field

¹ *Loc. cit.*, pp. 114-115.

² See Ferree, C. E. and Rand, G., 'An Optics-Room and a Method of Standardizing Its Illumination,' *Psychol. Rev.*, 1912, 19, pp. 364-373; Rand, G., 'The Effect of Changes in the General Illumination of the Retina upon Its Sensitivity to Color,' *ibid.*, pp. 463-490; 'The Factors that Influence the Sensitivity of the Retina to Color: A Quantitative Study and Methods of Standardizing,' *Psychol. Rev. Monog.*, 1913, 15, No. 62, pp. 79-166; see also Ferree, C. E., 'Tests for the Efficiency of the Eye Under Different Systems of Illumination and a Preliminary Study of the Causes of Discomfort,' *Trans. Ill. Eng. Soc.*, 1913, 8, p. 51.

illuminated by the tungsten lamp is deep orange in color, while the comparison field illuminated by daylight is clear white. This difference in color tone makes the judgment of equality of brightness difficult to make, and renders the instrument extremely insensitive for daylight work.

So far as the type of judgment is concerned, the method we are about to describe is in reality an equality of brightness method but it has the important advantage that the observer is never required to judge impressions differing in color quality. In making a photometric balance by this method, the feature is thus eliminated which has from the beginning of the work of measuring light intensities rendered the equality of brightness method difficult of application to heterochromatic photometry. Because of this factor we have at the suggestion of certain photometrists undertaken to work out the principle on which the method is based in a way that will be of general service to the work in heterochromatic photometry and to secure data on the points in terms of which a verdict is rendered for every method of photometry, namely, the sensitivity and precision of the method, and the agreement of its results with those obtained by the equality of brightness method.

The method is based upon the extreme sensitivity of the peripheral retina to brightness contrast, especially to the induction of black by a white screen. Not only is the peripheral retina extremely sensitive to brightness contrast, but, which is the crucial point of the method, very small changes in the illumination of the contrast screen produce a change in the amount of the contrast. That is, for any part of the retina, for example, the amount of contrast induced by the surrounding field upon a contrast stimulus increases with decrease of illumination. In the peripheral retina we have an extreme case of this. In this part of the retina very small changes of illumination indeed are required to produce a noticeable change in the amount of contrast induced, especially when the surrounding field is white and the stimulus is a gray of the proper brightness.

The apparatus needed for the method consists of a vertical

screen 60×50 cm. with an opening 15 mm. in diameter midway between top and bottom and 16 cm. from one edge, a motor to carry the measuring discs, and a photometer bar. The surface of the screen is covered with Hering mat white paper, or preferably with a paper overlaid with magnesium oxide deposited from the burning metal. This screen is graduated in the horizontal meridian from the center of the 15 mm. opening. Over the opening between the white covering and the screen is placed the gray which is to serve as the contrast-stimulus. Nos. 3-5 of the Hering series of standard gray papers were found to serve this purpose best for the intensities of light we used in the work the results of which are given in Table I. The measuring discs were made up of a sector of the same gray as was used for the contrast-stimulus and a sector of black, the varying proportions of which produce the match which is needed between the stimulus gray darkened by contrast and the measuring disc. The measuring disc was carried by a motor the shank of which is at one end of the screen and normal to it. When in position, the inner edge of the disc extends approximately to the 20° point of the graduations, and is about 3 cm. in front of the screen.¹ Immediately in front of the disc and 25° from the center of the stimulus-opening to the temporal side is placed the fixation-point.² The photometer bar was placed in a

¹ The measuring disc was placed this distance in front of the screen partly to give freedom of rotation but primarily to eliminate any induction by the screen on the disc. That induction is not present in any considerable amount under the conditions described above, is evident from the following considerations. (a) It is not directly detectable by the eye; and (b) a very high sensitivity is attainable by the method which could not be the case were induction present to any degree, for if it occurred in amounts great enough to influence sensation, the effect would obviously be to lower the sensitivity of the method. That there has been no lowering of sensitivity from this cause is rendered probable by the fact that approximately as small differences can be detected for lights differing in color quality as can be detected by Lummer-Brodhun photometers of the most improved type when the lights compared are of the same color quality.

² Care should be taken not to place the fixation-point so far from the stimulus-opening that the color used is seen of a different quality at this point than at the stimulus-opening. If this should occur for any color when the fixation is at the 25° point, a lesser excentricity should be chosen. The sensitivity of the contrast-effect to change of illumination is not lessened to any considerable extent, for example, by taking a 20° instead of a 25° fixation-point. We have found the 25° point to be very

plane normal to the screen midway between the stimulus-opening and the fixation-point. The contrast-stimulus and the measuring disc thus receive equal amounts of light from the source to be measured.

In Fig. 1 is given a picture of the apparatus in the rough form in which it is at present used. At *S* is shown the screen which is illuminated in turn by the standard and comparison lights; at *B* the photometer bar; at *D* the measuring disc; at *L* the lamp to be photometered; at *M* the mouthboard;

FIG. 1

and at *O* the opening filled with gray which is darkened in graded amounts by induction from the screen *S* as the amount of light received by it from the lamp *L* is varied. The screen *S* is supported by short rods screwed into heavy tripod bases. In order to provide for adjusting the height of the screen above the table the frame of the screen is fastened to the supporting rods by means of a collar and set screw. On the upper edge of this frame is attached a device for lining up the eye with the stimulus-opening *O*. This device consists of the following parts: A vertical arm carrying at its lower end a small circle 15 mm. in diameter extends satisfactory, however. For a fixation-point we used a black knot on a gray thread, stretched from a point on the screen *S* to a rod in front and on the opposite side of the measuring disc.

down to the level of the stimulus-opening *O*. Attached to the vertical arm just above this circle is a horizontal arm 15 cm. long which carries at its outer end and at right angles to it a disc 22.3 mm. in diameter. The size and position of the disc, the circle, and the opening *O* and their distances from each other sustain such relations that when the eye is in position 25 cm. in front of the opening *O*, the line of regard contains the centers of the opening *O*, of the circle, and of the disc; and the inner edge of the circle is just contained within the stimulus-opening; and the edge of the disc is just contained within the circle. That is, in effect the device is a peep-sight arrangement, and the alignment described above is possible only when the eye is in such a position that the line of regard is perpendicular to the stimulus-opening, the circle, and the disc at their centers. The device is attached to the metal frame by means of a screw with a milled head, so that after the alignment is made it can be readily turned out of the road and clamped. In order that the distance of the eye may be accurately adjusted at the same time its alignment is made with the stimulus-opening, a measuring device is also provided. This device consists of a slender brass rod 25 cm. long fitted at either end with two short right-angled arms 5 mm. in length. On the end of one of these arms is a ring which is just larger than the stimulus-opening, and on the other is a brass disc of the same diameter as the ring, provided at its center with a large pupillary aperture. In adjusting the distance of the eye this disc is rested lightly against the forward surface of the eyeball and the ring against the screen *S* concentric to the stimulus-opening. When the position of the eye is once determined, a mouthboard is adjusted and clamped in position so that the observer's teeth fit into impressions previously made and hardened in wax. This fixes the relation of the observer's eye to the stimulus-opening *O*. All that is needed, therefore, at subsequent sittings to bring the eye again into this relation, is to fit the teeth into the impressions on the mouthboard. As stated above, the photometer bar when adjusted stands in a plane normal to the screen *S* and midway between

the stimulus-opening and the fixation-point. This guarantees that the stimulus-opening and the measuring-disc at the fixation-point shall receive equal amounts of light from the lamp on the bar. The nearer end of the bar is placed at a distance below the level of the center of the stimulus-opening and fixation-point equal to the height of the center of the filament of the lamp above the bar. Owing to the fact that the head may cast a shadow on the stimulus-opening when the bar is horizontal, the rear end of the bar is raised until the stimulus-opening and the screen for some distance around are free from shadow for any position of the lamp on the bar that may be needed to obtain the photometric balance. In order to provide for this tilting, the bar is made adjustable in height. It is supported on two heavy tripod bases each carrying a vertical stem made of hollow tubing split at the upper end and provided with collar and set screw. Into these tubes fit rods attached to the photometer bar by means of hinge joints. This arrangement permits of an independent adjustment of the height of the two ends of the bar. In order that a given amount of slant may be reproduced at any subsequent observation, an attachment is provided to indicate the angle which the bar makes with the vertical. This consists of a graduated half circle attached just above the hinge joint to the supporting rod furthest from the screen. On this rod just below the hinge joint is fastened a pointer. When the further end of the rod is raised this half circle is rotated past the pointer and the amount of rotation may be directly read from its graduated limb. Since the angle at which the bar is tilted is kept the same for the comparison and standard lights, the tilting interferes in no way with the accuracy of the photometric balance or the application of the law of squares to the determination of the relative luminosities of the standard and comparison lights.¹

¹ We hope soon to use the principle upon which the method is based in connection with apparatus which will be more conveniently applicable to the general needs of the photometrist than is the rough device which is described above. One of the improvements which we expect to make, for example, is to eliminate the need of a slanting bar. For while the slanting bar does not interfere with the establishment of a correct photometric balance at the screen, it is not the most favorable condition under

The method is applied as follows: The observer's eye is lined up with the stimulus-opening in the manner described above and the contrast stimulus is put in position. The standard lamp is placed on the photometer bar at a given distance from the screen, the eye is turned out to the fixation-point and the sectors on the measuring disc situated just back of the fixation-point are adjusted by means of a number of separate judgments to match the gray at the stimulus-opening darkened by contrast.¹ The relative value of these sectors becomes the index of the illumination of the screen for the standard lamp at the given distance. The standard lamp is then removed, the comparison lamp is placed on the bar, and its position is adjusted

which to operate all types of lamps. This should not be difficult to do by moving the observer farther from the screen and using a correspondingly larger stimulus-opening and a greater linear distance from this opening to the fixation-point.

¹ That is, with the change in the amount of light falling on the photometer head made up of gray stimulus and surrounding screen of white, there is a change in the amount by which the gray stimulus is darkened by contrast from the surrounding screen. This amount is recorded on the measuring disc directly behind the fixation-point, by adding a sector of black to the gray sector, which was chosen, it will be remembered, of the brightness of the gray stimulus uninfluenced by contrast. The value of this black sector thus becomes the fixed index of the amount of light falling on the screen in any given case. In short, with a given brightness relation of contrast stimulus to surrounding screen, there is a finely graduated scale of contrast values inversely correlative with the amounts of light falling on the screen. That is, with a large amount of light or high illumination of the screen, the amount of contrast induced is low; with a small amount of light falling on the screen the amount of contrast induced is high. The amount of change of the illumination of the screen needed to produce a noticeable change in the amount of contrast induced is very small indeed, and because of this the method possesses a high degree of sensitivity. So far as we are able to determine, the amount of change in this illumination required to produce a just noticeable change in the contrast sensation is no greater than is needed to produce a just noticeable change in the positive sensation under the best conditions that have been as yet devised in photometric work for making the judgment, namely, the conditions presented by the Lummer-Brodhun photometer heads of the most improved type when the lights compared are the same in color quality. If this were not true, the method could not show, as it does, as great sensitivity for lights either the same or differing in color quality as does the equality of brightness method for lights of the same color quality. Also so far as we have been able to determine there is no greater variability in the eye's sensitivity to contrast from day to day than there is in its sensitivity to brightness itself. That is, photometric determinations by this method of a given light density on the screen show a very small mean variation from day to day, quite comparable in fact, with the mean variation found in judgments of brightness equality, when there is no difference in color quality to confuse the judgment. There is, moreover, so far as we have applied the method, a comparatively small variation for different observers.

until the contrast-stimulus again just matches the measuring disc. Since the proportion of sectors has not been changed from that which was determined for the standard lamp, it can be assumed that the illumination of the contrast screen is again of the same value it was for the standard lamp at the given distance. The comparative luminosities of the two light

TABLE I

SHOWING A COMPARISON OF THE RESULTS OBTAINED BY THE CONTRAST AND EQUALITY OF BRIGHTNESS METHODS

Source of Colored Light ¹	Color	Distance of White Light Giving Equality of Illumination		Sensitivity or Amount of Change that Can be Detected by				Precision or the Mean Deviation from the Average			
		Equality of Brightness Method		Equality of Brightness Method		New Method		Equality of Brightness Method		New Method	
		Cm.	Cm.	Cm.	Percentage (Candle-power)	Cm.	Percentage (Candle-power)	Cm.	Percentage (Candle-power)	Cm.	Percentage (Candle-power)
87 cp. 41 cm. distant from photometric screen	Red	66.1	66.6	2.0	5.6	0.5	1.3	1.1	3.2	0.20	0.55
	Blue-green	59.5	59.5	2.5	7.85	0.5	1.65	1.5	4.85	0.22	0.97
52 cp. 38 cm. distant from photometric screen	Red	82.2	82.2	2.1	5.0	0.5	1.1	1.1	2.5	0.20	0.41
	Blue-green	70.9	70.5	4.0	10.4	0.5	1.4	2.0	5.5	0.25	1.1
13 cp. 38 cm. distant from photometric screen	Red	160.6	160	3.0	3.7	0.5	0.65	1.6	1.9	0.23	0.3
	Blue-green	134.5	134.9	4.0	5.7	0.5	0.76	2.2	3.2	0.24	0.46

sources, thus, can be computed directly by the law of squares from distance readings on the photometer bar. The advantage of the method for color photometry is, as has already been pointed out, that in the judgment in case of both the standard and comparison lights, the surfaces, the brightness values of which are being compared, are both illuminated by the same light. The eye is thus never compelled to make its judgment of two surfaces differing in color quality. The method is in fact almost if not quite as sensitive for the

¹ The colored lights were obtained in these experiments by means of the Wratten and Wainwright filters inserted in openings in the front of lamp-houses. The red filter used transmits the spectrum from $.768 \mu$ to $.65 \mu$; and the blue-green from $.52 \mu$ to $.465 \mu$.

photometry of lights differing in color quality as it is for the photometry of lights of the same color quality or for colorless light; and its sensitivity for lights of the same color quality or for colorless light compares very favorably, by test, for the same observer with photometers of the best Lummer-Brodhun type. The indirect vision judgment, it may be said, however, presents more difficulty to the unpractised observer than is afforded by the flicker judgment, but this difficulty yields rather readily to practice. The method has been in almost daily use in our laboratory for four years. It has, for example, been employed exclusively for the standardization of the illumination of our optics-room in the determination of color sensitivity.

Table I. has been prepared to show a sample of a comparison of the results of this method and the equality of brightness method. These results are typical. They report the average of twenty-five determinations. Sensitivity and the average deviation or precision are expressed both in divisions of the photometer bar and in percentage candle-power. The lamps used for this work were standardized by the New York Electrical Testing Laboratories. They were operated on a storage battery circuit.

With some modifications the contrast principle described above can be used for the determination in terms of pigment standards of the white-black value of colored papers for a given degree of illumination of the papers. The method of doing this can perhaps best be explained by comparing it with the method just described. In this method, it will be remembered, we determined how much contrast would be induced by one surface upon another of a lower coefficient of reflection when a given amount of light was incident upon the two surfaces, and used this amount of contrast as an index of the amount of light falling upon the two surfaces in establishing the photometric balance, or equality of illumination at the screen. Here the relation of coefficient of reflection of the screen to the stimulus is fixed and the amount of light falling on the screen from the comparison lamp is varied until the right amount is obtained to give the photometric balance with the

standard lamp. In the determination of the white-black value of a colored paper under a given illumination, the situation is a little different. The amount of light falling on the screen is kept constant and the relation to the screen of the pigment standard which is to express the white-black value of the color, must be varied until the right one is obtained. Here again we find out how much contrast is induced by one surface upon another of a lower reflection coefficient, in this case the colored paper; and this amount of contrast is taken as an index of the brightness relation of the colored paper to the surface of higher reflecting power, the screen *S* in Fig. 1, for the given intensity of illumination. The problem thus becomes to determine what gray sustains the same brightness relation to the screen *S* as does the colored paper. This gray should represent the white-black value of the color.

In detail the method is as follows: The stimulus-opening *O* is filled with the colored paper for which the determination is to be made and a disc of the same color is made a part of the measuring disc. The fixation is taken and black is added to the color on the measuring disc until it is sufficiently reduced in brightness to match the stimulus color darkened by contrast. The amount of black that has to be added becomes the index of the amount of contrast induced and therefore of the brightness difference between the screen *S* and the colored paper for the degree of illumination used, and is kept constant during the remainder of the work. In order to be able to find out what gray differs as much in brightness from the screen as does the colored paper, a disc made up of variable proportions of white and black is substituted for the colored stimulus behind the screen; and a sector made up of variable proportions of the same white and black, for the colored sector on the measuring disc. The white and black are then varied in proportions which are carefully kept equal for stimulus and sector until a match is obtained. When this match is gotten the relative amounts of white and black either in the stimulus disc or the substitute sector on the measuring disc should give the gray value of the color for the illumination employed. That is, there is obviously only one

gray that could be used in place of the contrast stimulus and in the substitute sector in the measuring disc which would satisfy the conditions of the experiment, and that is a gray having the luminosity or white-black value of the color originally used. It is scarcely necessary to caution that throughout the determination the light falling on the screen, the stimulus and the measuring disc must be kept constant. Care must be taken also in this case not to take the fixation so far from the stimulus-opening that a color difference is present between stimulus and measuring disc.

If the determinations are wanted in photometric units they can be gotten by the equality of brightness method from the grays which have been equated with the colors. A convenient instrument to use for this purpose is the Sharp-Millar portable photometer with its scale calibrated to give results in terms of candle-power per sq. in. The calibration can be readily made by the experimenter from a magnesium oxide surface with a known amount of light falling on it. If the light incident on the grays is daylight, the same difficulty will be experienced with the Sharp-Millar photometer, however, which was mentioned earlier in the paper, namely, the two halves of the photometer field will differ in color quality due to the fact that the carbon standard in this instrument gives a light rich in the long wave-lengths.

¹ In discussing the application of this method to the determination of the brightness of colored papers, reference should probably be given to the discussion of the Talbot-Plateau law in the paper preceding this. (See Ferree and Rand, 'A Preliminary Discussion of the Deficiencies of the Method of Flicker for the Photometry of Lights of Different Color,' *Psychol. Rev.*, 1915, 22, pp. 149-150.)