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ON THE PHOTOMETRY OF DIFFERENTLY COLORED LIGHTS AND THE "FLICKER" PHOTOMETER.[1]

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IN November, 1893, during measurements on some colored disks, it became necessary to know the relative luminosities of the colored papers employed. An attempt was first made to estimate the luminosity directly by comparison with Maxwell disks of black and white, smaller in diameter, and mounted on the same axis. The relative proportions of black and white were changed until, on rotation, they formed a gray, which was estimated to be about equal in brightness to the colored disk under examination. This method, practiced by certain experienced observers, doubtless has afforded good results, but in my hands proved difficult and uncertain.

Trials were then made by four other observers, all somewhat skilled in physical measurement, whose general color-sense was found to be similar, but their estimates of luminosity were found to vary in such an irregular fashion as to make any comparison impossible.

Later experiments, carried out with the help of some thirty undergraduate students, led to similar results. Differences of 50 per cent between two different observers frequently arose,

[1] Read at the Springfield meeting of the A. A. A. S., Aug. 30, 1895.

when the light to be compared differed no more than an ordinary from a Welsbach gas-burner; while the same observers, working with light of the same color, would agree at least within 2 or 3 per cent.

By practice the margins of difference may be rendered smaller, yet experts often differ in their estimates of the brightness of arc lights when compared with standards of different color; and it is questionable whether one can always be sure that by practice in such measurements he gains greatly in accuracy. His measurements agree with each other better than at first, but if his method of comparison have in it something of an arbitrary or personal quality, as it must from the very nature of the case, it remains uncertain whether he may not be fixing himself in an erroneous practice rather than approaching a correct one.

The character of these results, and the need of some more exact method of comparing color-luminosities, led to the consideration of Professor Rood's "flicker" experiments.[1]

Rood prepared about fifty gray disks differing successively, as equally as possible, in depth of tint from black to white. If a dark shade was combined with a light shade in the usual way, and rotated rather slowly, the familiar unpleasant sensation known as a flicker was produced; but if successive pairs, more and more nearly alike, were chosen, the flicker became less, until it almost or quite disappeared. Nearly the same effect was produced if, instead of a gray, some other color was substituted on one of the disks. It was always possible to combine with it a gray disk of such a shade that the flicker nearly ceased, showing that this sensation is apparently independent of the wave-lengths of the lights compared, and dependent only on their relative luminosities. Professor Rood suggests that the principle may be easily applied to ordinary photometric work, but indicates no method. The special arrangement described in his paper serves admirably to compare pigments, when in such form that they can be spread upon disks and mounted in the whirling machine.

For ordinary photometric purposes, however, there is necessary some arrangement by which luminosity can be varied continuously

[1] American Journal of Science, Vol. XLVI., September, 1893.

instead of step by step, as with a set of gray disks, which can be mounted on a photometer bar so as to compare colored lights as well as colored pigments, and which is reasonably quick and convenient in use. No doubt there are many ways of applying Professor Rood's flicker principle; the one which I, after some trial, found most successful was as follows: —

A card was cut in the shape *AHBG*, in the figure, so as to form two semicircles of about 5 and 8 cm. radius respectively, joined along a common diameter. This could be rotated at any desired speed about the axis *K*, in earlier experiments by clock-

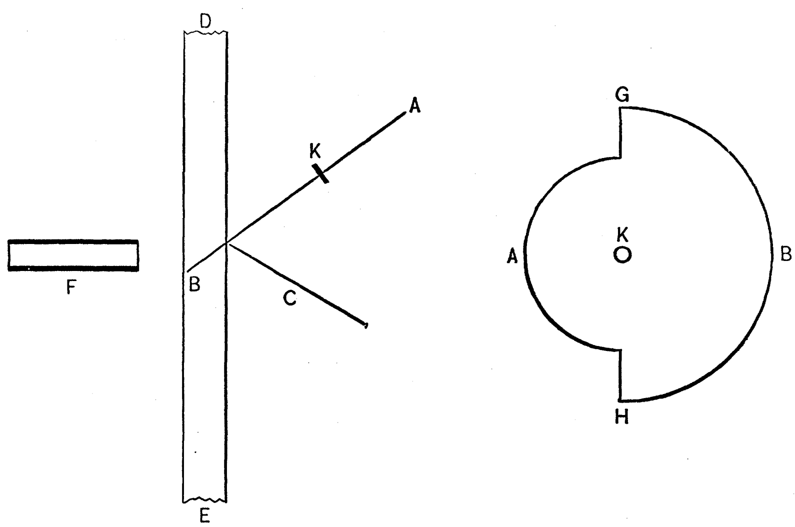

Fig. 1.

work, but afterward, and more conveniently, by hand. A diagrammatic plan of the apparatus as used is shown in the figure. *DE* represents the photometer bar, *AB* is the revolving disk, *C* is a card, which may be white or colored with any pigment which it is desired to study, *F* is a tube through which the observer looks. It is evident that when the apparatus is in the position shown in the figure, the outer portion of the revolving disk only will be visible through the tube, but when the disk is rotated half a turn, the small semicircle will not come into view at all, and the observer will see only the card *C*. As the disk revolves, the two pieces will be presented to the eye in rapid succession, and, if they differ in luminosity, will produce the sensation of "flicker." If equal lights are placed at the ends of the photometer bar, the relative illumination of the card and disk can be varied by sliding the photometer along the bar. The flickering sensation can thus be entirely destroyed, whatever the colors are upon the card and disk. (Various colors were tried upon the disk, — red, white, and different grays, — but white was finally adopted as in all cases the most convenient.) When the proper position of the photometer was reached, not only did the flicker vanish, but the sense of color in the field of vision became much weaker or entirely disappeared, so

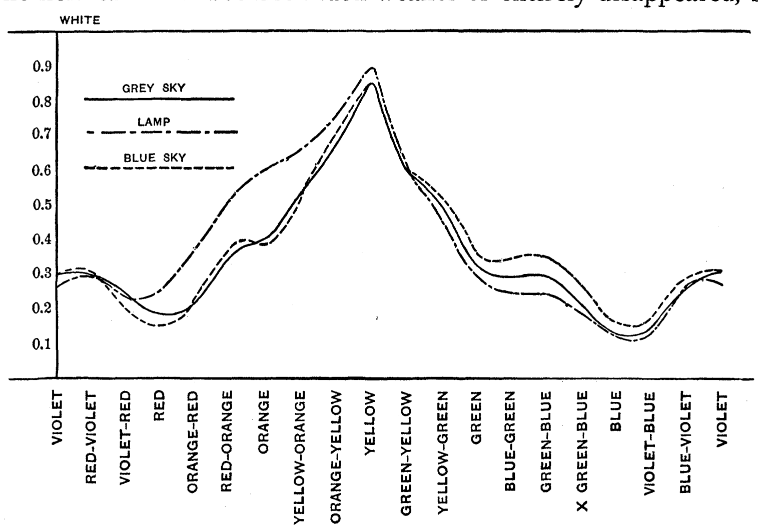

Fig. 2.

that it was frequently difficult or impossible to tell what color was upon the card. A slight movement of the photometer in either direction revived the sense of color and reëstablished the flicker. The results obtained with this instrument were surprisingly good in ease, rapidity, and precision.

Work was interrupted at this point until May, 1895, when the measurements were taken up again, and the instrument itself somewhat carefully studied.

The colors used for experiments on pigments were chosen from the well-known series of colored papers made by the Milton Bradley Company of Springfield, Mass., and included the whole range of the spectrum. These papers were pasted upon perfectly flat cards, and placed successively in the position marked *C* in the figure. Three curves are shown to illustrate the capacity of the instrument, exhibiting the relative luminosities of these nineteen colors, when illuminated by the light of a kerosene lamp, of a dull gray sky, and of a bright blue sky.

The predominance of the lamp-curve toward the red end of the spectrum and of the clear sky at the other end is manifest, while the similarity of the curves shows that the measurements are of like character and definiteness, whatever the source of illumination. In all these cases the revolving disk was white, lighted by a lamp, while the colors on the card were exposed to the light under investigation. Since the flicker effect is independent of the wave-length, any source of light which is constant may be used to illuminate the disk without changing the results dependent on the luminosity of the colored card. The curves from sky light and cloud light, though the mean of several trials, were not entirely satisfactory on account of the comparatively inconstant brightness of these sources of light. The observations on lamplight, however, were made twice, at an interval of over two months, with practically identical results.

A greater interest, perhaps, lies in the instrument itself. An apparatus so new, and depending on a physiological principle which has been so little studied, presents many points for investigation, before its utility as a practical photometric apparatus is assured. The remainder of this paper is occupied with a study of some of these points.

1. The precision of setting, as compared with other types of photometer, was tested in over one hundred settings on nineteen different colors. The difference between two successive readings was seldom more than one per cent, though a few readings differed as much as two or three per cent. As these readings were made over the whole range of the spectrum, it seems fair to say that the instrument can be used upon lights presenting the widest differences of wave-length, with a precision approaching that of ordinary types of photometer when comparing lights of the same color.

2. Since the photometer depends, not on the actual comparison of like quantities, but on the distinctness of a peculiar physiological sensation, — the flicker, — it is worth while to see whether different observers will agree. To test this question, and incidentally to try the instrument with colored lights instead of colored papers, both disk and card were made white, and equal lamps, the colors of which could be changed at pleasure by the interposition of colored glass, were placed at the ends of the photometer bar. Two observers, whose eyes were known to be similar, compared successively the brightness of the two naked lamps, first by an ordinary photometric method, then by the flicker. A red glass was then placed in front of one lamp, a green glass in front of the other, and the same observations were made again. One of the two observers had never seen the instrument before. The results follow, each being the mean of four or five concordant observations. The actual readings are given in feet and hundredths, not reduced to comparative luminosities. One lamp stood at 3.00, the other at 9.00 on the photometer bar.

Observer F.		Observer W.	
Ordinary.	Flicker.	Ordinary.	Flicker.
Both lights naked.			
5.98	5.96	5.98	5.98
Left lamp red, right green.			
5.59	6.79	6.08	6.88

Thus, in the last case, the setting of F by direct estimation differed from that by flicker by 1.20 feet, that of W by 0.80 foot.

The setting of F by estimation differed from that of W by 0.49 foot; while F's flicker setting differed from W's by only 0.09 foot. The last disagreement is comparable with the errors of observation.

At a later time, three other observers, making comparisons for technical purposes between coal-oil lamps and a standard candle which differed from them somewhat in color, were able with the flicker photometer to obtain accordant results among themselves much more easily and surely than by ordinary methods.

3. Two "disks" like those in the cut were mounted on the same axis in the photometer. By sliding one upon the other, the fraction of a revolution during which the card was visible could be varied between 180° and 0°. The relative length of exposure of the eye to the two lights could thus be varied within wide limits. Several comparisons were made of lights differing widely in color, and with openings from $22\frac{1}{2}°$ to 180°, but no differences in reading were observed that could be traced to this cause. While it is true that the sensitiveness of the retina differs for lights of different wave-lengths, and probable that differently colored lights require different periods of time to produce equal sensations in the eye, it appears from these experiments that there is time, at the comparatively slow rate of rotation of the disk, for every color to produce its full effect, so that errors which might be produced by irregularity in rate of rotation or in shape of the disk are negligible.

4. In much of the work, the photometer and the standard lamp were kept at fixed points, and the balance obtained by moving the other light, thus making all comparisons at the same actual degree of illumination. This method of using any photometer has some obvious advantages, though the sensitiveness is not quite so great as when the photometer itself is moved. To determine whether the absolute brightness has any effect on the settings, measurements were made of six colors — red, orange, yellow, green, blue, violet — under widely differing illuminations. When the light was faint the measurement became much more difficult, but the results obtained with bright and faint light did not appreciably differ, showing that the well-known greater sensitiveness of the eye to blue light is not important in measurements made under conditions proper to this photometer. When the illumination is small the flicker is very faint and may be invisible while the photometer is moved over as much as 6 or 8 cm., but by reading the points each side of this space where the flicker again becomes visible, and taking the mean of the two readings, results may be obtained almost as trustworthy as with brighter light. It should be remarked that this method in general depends for its value somewhat on the state of the eye. It appears certain that

two normal eyes, in a reasonably fresh condition, would obtain like results, but if the eye is wearied from long-continued observation or loss of sleep, the perception of the flicker becomes more difficult, and the difficulty appears to vary with different colors in a way that has not yet been studied.

5. The question still remains, whether the flicker method gives in all cases a true measure of luminosity comparable to that which would be obtained by any more direct photometric method. To test this, the luminosity measures afforded by Maxwell's disks were used.

Suppose, for example, three colors — say red, green, blue — combined on the whirling machine into a neutral gray, which is matched by the combination of a black and a white disk. The amount of white in the latter combination, corrected for the white light reflected by the black portion, is of course the measure of the luminosity of the colored disk in terms of white, which quantity, again, is dependent upon the luminosities of the three colors of which it is composed.

If now the fraction of the whole circle occupied by any color is multiplied by its luminosity as measured with the flicker photometer, the result will be the amount of white equivalent to that colored sector, and the sum of the results obtained by treating each of the colored sectors in this way should equal the amount of white in the black and white disk. Two examples are given below. The circumference of the disk was divided into one hundred equal parts, so that the numbers given are direct percentages of the whole circle.

The upper row of figures in each case is the ordinary color-disk equation. The second is the luminosity of the given colors referred to white, as measured by the flicker, the lower line gives the product in each case. The sum of these products given under white should be the same as the white in the upper row, which is the corrected reading from the black and white Maxwell disks.

	Red.	Green.	Blue.	White.	Red.	Green-Yellow.	Blue.	White.
Color-equation	40.5	49.2	10.3	22.6	18.5	34.0	47.5	30.4
Luminosity	0.238	0.295	0.106	—	0.238	0.617	0.106	—
	9.64	14.50	1.09	25.23	4.41	20.96	5.03	30.40

Fourteen such trials were made with different colors, the results differing by one to three per cent from exact equality.

Summary.

The flicker photometer used to compare lights of any color approximates in convenience and accuracy any of the ordinary photometric appliances used with lights of the same color. Different observers whose vision is normal obtain like results.

Irregularities in the division of the disk or the rate of rotation are without appreciable effect on the precision of the measurements.

Differences in the absolute brightness of the lights compared present no greater difficulties than in any photometric method.

The instrument gives a true measure of luminosity comparable with that obtained in other trustworthy ways.

ADELBERT COLLEGE, Nov. 1, 1895.