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ON THE GROWTH AND DECAY OF COLOR SENSATIONS IN FLICKER PHOTOMETRY.

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Introduction.

NOTWITHSTANDING the extensive investigations in heterochromatic photometry the photometrician is still unable to equate brightnesses widely different in color with surety. This is due chiefly to the fact that the two practical methods of photometry—the flicker and the direct comparison methods—do not give concordant results. It is therefore necessary besides establishing an "average eye" to determine which method shall be the standard.

Since the flicker photometer was first proposed as a means of overcoming the difficulties attending a large color difference in photometry, it has won many supporters. But in the light of the work that has been done recently it is plain that those who had accepted the flicker photometer had done so before it had been thoroughly investigated. H. E. Ives[1] has perhaps investigated the two practical methods of photomery in parallel more extensively than any other investigator. Among other interesting data gathered in that investigation it was shown that the flicker method was not subject to the Purkinje effect but to a reversed effect. The writer[2] verified this and incidentally showed that the ratio of a red light to that of a blue-green light as measured was far different depending upon the method. In the present work it was found after balancing a red light and a blue-green light individually against total tungsten light by the direct comparison method, that the intensity of the red light must be reduced to 55 per cent. of its foregoing value in order to balance by the flicker method the foregoing intensity of the blue-green light. This result agrees closely with that obtained in the

[1] Phil. Mag., 1912.

[2] Electrical World, March 22, 1913; London Illuminating Engineer, Vol. 6, p. 119.

previous work. Ives's data show this difference in the results by the two methods although it was not discussed or pointed out in the original paper. This difference and the fact that the flicker photometer is subject to a reversed Purkinje effect are sufficient to show the importance of investigating the possible causes for the discordance in the results by the two methods. It is apparent at once that the physiological phenomena occurring in the two methods are not wholly the same, for only in the direct comparison method is simultaneous contrast effective. Further, the flicker method is probably complicated by after images and the different rates of growth and decay of the various color-sensations.

Apparatus.

An apparatus was constructed so as to include both a flicker and a direct comparison photometer in such a manner that by intercomparison certain data could easily be obtained without introducing uncertainties which might arise in using two instruments. The apparatus is shown diagrammatically in Fig. 1. The photometer consisted of a two-part

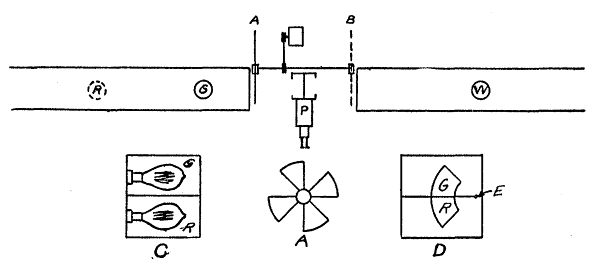

Fig. 1.

Combined Flicker and Direct Comparison Photometers.

field (a circular field about 10°, bisected vertically) one side of which could be converted into a flicker photometer field. Direct comparison could therefore be made of a flickering field against a steady field or the instrument could be used either as a flicker photometer or a direct comparison photometer. *G* and *R* are lamps movable on a two-compartment track whose cross section is shown at *C*. *D* is an end view of the compartments near the sector disk *A*. At *G* and *R* in *D* are placed respectively a blue-green and a red glass over ground opal glasses. These colored glasses whose transmission curves are shown in Fig. 2 were purposely selected nearly complementary to each other in order that little color difference would remain when the lights were mixed and compared with the tungsten standard light *W*. The sector disk *A* rotating about the center *E* causes one side of the photometer field to be a flicker photometer field. The sector disk (50 per cent. opening) was covered with black velvet to eliminate reflected light. Tungsten lamps at *W* were used as standards. The lamp *G* was kept in one position throughout the measurements, the balances being obtained by moving either *R* or *W*.

Much of the data obtained by means of this apparatus was for purposes of verification of the outstanding difference in the results by the two methods and a study of the fundamental axioms which must underlie any correct method of photometry. Not all of these data are reported

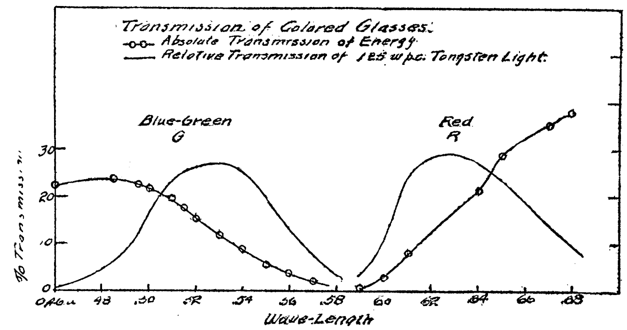

Fig. 2.

in the present work, some of it having been reserved until other observations can be made. However in order to illustrate more fully the adaptability of this apparatus to the general problem a regular series of observations will be described. First *G* was set at a certain position and with the sector disk removed a series of settings were made in which *G* was balanced against the standard lamp *W* by the direct comparison method. *W* was set at the mean value thus obtained and *R* was balanced against it. *R* was then set at the mean value just obtained and with *G* also lighted and with the 50 per cent. sector *A* now rapidly rotating this mixture was balanced against *W* by varying the position of *W*. Next *R* was balanced against *G* by the flicker method by varying the position of *R*. Finally *R* was balanced against *W* with a red glass interposed between the latter and the photometer, the balance being made by varying the position of *W*. It was then possible to match *G* against *R* by the direct comparison method. The mean values of a number of such series yielded interesting information regarding the two methods.

The measurements were made in all cases unless otherwise noted, at an illumination of about five meter-candles upon the photometer screen computed from the position of *W*. In the former work[1] with the same photometer it was found that at an illumination above one meter-candle

[1] Electrical World, March 22, 1913; London Illuminating Engineer, Vol. 6, p. 119.

no complications arise from the Purkinje or reversed effect; that is both methods give the same results as at higher illuminations. However at an illumination somewhat lower than one meter-candle on the photometer screen results varied considerably from the values at higher illumination.

On Mixing Colored Lights by the Flicker Method and by Superposing Steady Lights.

An experiment was performed to ascertain if there was any difference in brightness on mixing the two colored lights by the flicker method and by superposing the steady lights. The colors being nearly complementary to each other the color difference in these measurements was small. When the colored lights were mixed by means of a sector disk the speeds of the latter were slightly above and below that at which flicker vanished. The sector disk was also rotated at a very high speed and finally was taken out and the lights permitted to mix by superposition. In all cases the comparison was made against W with the same slight color difference. Practically identical results were obtained in all cases showing that there was no difference in brightness when R and G were mixed by superposing the two colored lights or as in the flicker method providing the flicker was not more than barely apparent. This supports the validity of Talbot's law for colored lights.

On the Growth and Decay of Color Sensations.

It has long been known that the retina responds at different rates to lights of different color. Broca and Sulzer[1] have investigated the growth of luminous sensation for lights of various colors. Some initially far overshoot their final value while others barely exceed their final steady value. It was found that red, white, and blue overshoot considerably while green overshoots scarcely at all indicating that with green light there is either a very slight lag of fatigue behind impression or very slight retinal fatigue. A successful attempt was made to determine the maximum values of flickering lights at various flicker frequencies. A flickering field illuminated by R (Fig. 1) was compared with a steady red field and the maximum brightness of the flickering field was measured throughout a wide range of sector speeds. The same was done with the blue-green light G. In both cases the intensities of R and G were those resulting from a balance against W by the direct comparison method. These were the mean values of a large number of observations. The curves in Fig. 3 show the values of the maximum brightnesses of the

[1] Comptes Rendus, 1903, p. 137, 977, 1046.

two flickering colored lights (each flickering against darkness) at various flicker frequencies. It is to be noted from these curves that flicker disappears at a lower speed for the blue-green light *G* than for the red light *R*. With the intensity of *G* unchanged from its foregoing value *R* was balanced against it by the flicker method. The speed of the sector disk necessary in this case was 12 cycles per second as indicated in Fig. 3. It will be noted that the maximum brightness of *R* at this speed is greater than that of *G*. Of course the flicker in each case shown in the curves was *R* or *G* against black while with the flicker photometer it was *R* against *G*. It must not necessarily be supposed that when the intensities of *R* and *G* are such that their flickers against black disappear at the same speed, that they will balance each other by the flicker method. However it appears from Ives's data and also from the writer's data that this is nearly if not absolutely true for the conditions under which these experiments were made. The results of this experiment combined with

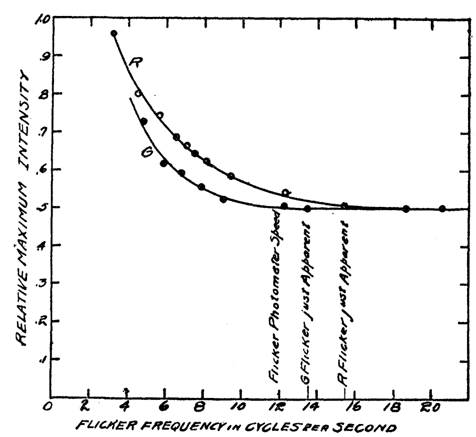

Fig. 3.

Maximum Brightness of a White Surface Illuminated by a Flickering Colored Light.

those which follow indicate quite strongly why the intensity of *R* when balanced against *G* by the flicker method must be decreased from its value as determined by a direct comparison measurement. The results shown in Fig. 3 were verified by many tests and while the eye seemed to vary in its sensibility to flicker very consistent results were obtained considering the difficulty in making such observations. An attempt was made to obtain the minimum brightness of the flickering lights but it was found that the maximum brightness was always so distracting in its effect that attention could not be riveted upon the minimum value. The curve representing minimum values would obviously start at zero and finally reach a steady value which would be, as in the case of maximum values, one half of the steady maximum value. The latter statement assumes the validity of Talbot's law for colored lights which was verified in this work. The effect of change of intensity is shown in Fig. 4. Here the intensities of the red and blue-green lights are approximately those determined by the mean of the results obtained by the two methods. It is seen that at the higher illumination there is an overshooting of the steady value which is taken as unity with the sector stationary and open. This overshooting is greater for the red light than for the blue-green

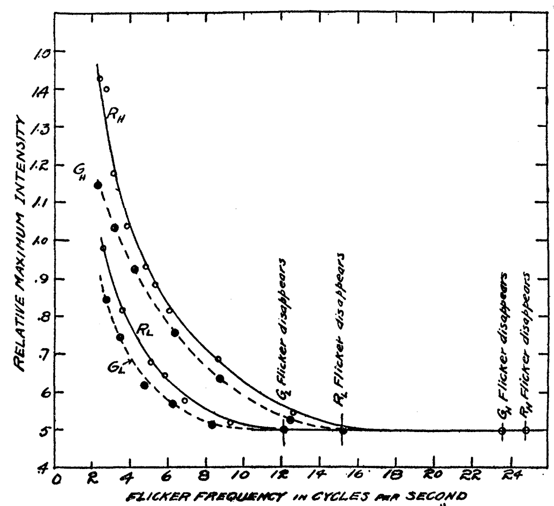

Fig. 4.

Showing the Effect of Intensity on the Maxima of a Flickering Light. Full Line Represents Red Light. Broken Line Represents Blue-Green Light. Subscripts Indicate High and Low Intensities.

light. As the illumination decreases the over-shooting becomes less marked. This is to be expected from the work of Broca and Sulzer which work however was done apparently in a different manner and without special consideration from the standpoint of flicker photometry.

Effect of After-images.

An arrangement, which is shown diagrammatically in Fig. 5, was devised to study the effect of after-images. Steady sources G_1 and R_2, respectively blue-green and red in color, as used throughout the work, were arranged to illuminate opposite sides of the photometer screen. Illuminations due to R_1 and G_2 of the same colors as the foregoing lights were arranged to be flickered by means of identical 50 per cent. sector disks, S_1 and S_2, rotating on the same shaft. By this means it was possible to flicker red light from R_1 on a steady blue-green field due to G_1 and compare this total brightness with that resulting from flickering blue-green light from G_2 on a steady red field due to R_2.

All observations were made without color differences. The procedure was as follows: R_1 and G_2 were taken the same as previously determined by the direct comparison method, then R_1 was balanced against R_2 with G_1 and G_2 extinguished, the sectors being open and stationary. Next R_1 and R_2 were extinguished and G_1 was balanced against G_2. Finally with all four lights turned on and with the sector disks rotating at a speed such that flicker was barely apparent the photometer field remained balanced as might be expected. However as the speed was reduced the side of the photometer field upon which R_1 was flickering apparently became much brighter; at least the maximum value of the brightness was considerably greater. Flicker upon this side of the photometer was very violent while upon the other barely apparent. A great reduction in the speed was necessary before the flicker upon the other side became very marked. In fact the illumination on the side where the blue-green light flickered appeared quite uniform as the speed was reduced long after the side on which the red light flickered, became violently agitated. This same phenomenon was noticeable to a much less degree after the steady lights were extinguished.

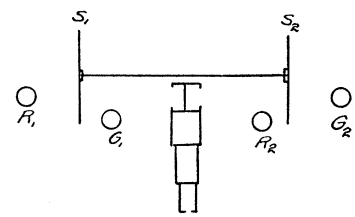

Fig. 5.

Apparatus for Superimposing a Flickering Colored Light Upon a Steady Light of Different Color.

Next, by combining certain features of the apparatus shown in Figs. 1 and 5, actual measurements were made of the maximum brightness attained by the red light flickering upon the steady green field and vice versa, the comparison source being a clear tungsten lamp W. The results are shown in Fig. 6. The intensities of the steady lights were twice the mean values of the flickering lights. The flicker photometer speed at this illumination would be about thirteen cycles per second in comparing the particular red and blue-green lights. When R and G were of such values as determined by the flicker method the above effects would have been greatly decreased in magnitude. In fact one could not be certain that under these conditions there was any difference in the flicker of the two fields. This experiment gives a strong clue to the reason for decreasing the intensity of the red light when it is balanced by the flicker method against blue-green light. The much greater agitation of the field consisting of a flickering red light and a steady blue-green light points very strongly to the conclusion that the red light is weighted more by the flicker method than by the direct comparison method because in order to obtain a balance the intensity of the red light must be diminished so that the flicker of *R* and *G* disappear at about the same speed. These data shown in Figs. 3 and 6 represent extreme experiments between which will be found the operation of the flicker photometer.

The difference in the rate of growth of sensation stimulated by lights

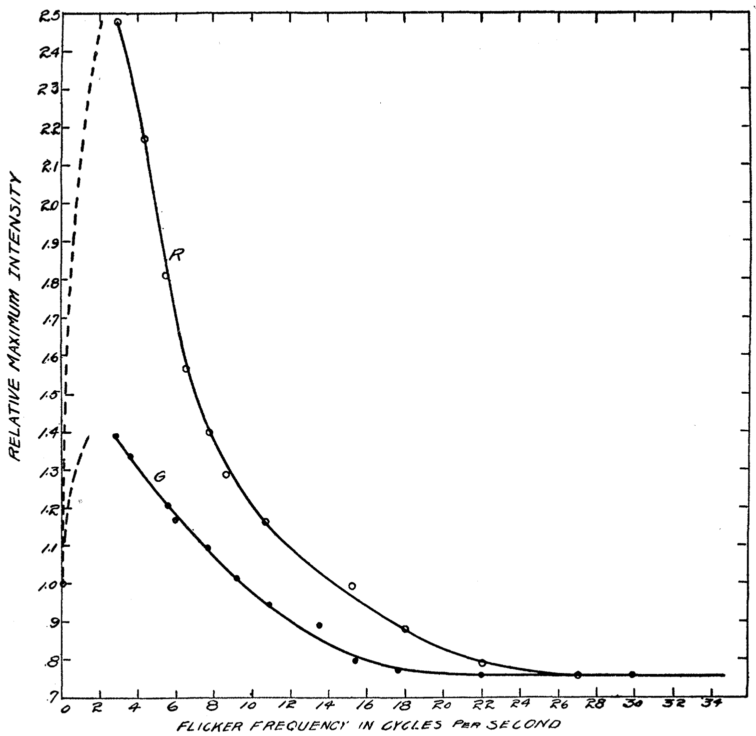

Fig. 6.

Maximum Brightness of a White Surface Illuminated by Superimposed Red and Blue-Green Lights, One of Which is Flickered. *R* Indicates Red Flickering on Steady Blue-Green Field. *G* Indicates Blue-Green Flickering on Steady Red Field.

of different color suggests the possibility that flicker photometers differing in design might not yield concordant results. The flicker photometer shown in Fig. 1 is of such nature that when balancing red light against blue-green light the color of the photometer field varies gradually from red through white to blue-green then to white and so on. In most flicker photometers the stimulus changes abruptly from one color to another. In the previous work[1] a Schmidt and Haensch flicker photometer was used. With that instrument the results obtained were not exactly the same as those obtained by the flicker photometer used in this

[1] Electrical World, March 22, 1913; London Illuminating Engineer.

work and reported in the first part of this paper. The writer cannot say that the difference in the results (which was not great) is due to the difference in the design of the photometers. However the effect of contour or wave-form of flicker may be of importance in flicker photometry.

On Vanishing-flicker Frequency.

The vanishing-flicker frequency (often referred to as critical frequency) is that frequency at which flicker vanishes when the light is rapidly alternated with darkness. This has long been known to vary with the intensity of the flickering light or brightness of the target. Kennelly and Whiting[1] state that "the vanishing-flicker frequency does not depend upon the mean illumination on the target: or at least only to a relatively small degree. It depends on the maximum and minimum cyclic illumination." They also conclude that "the vanishing-flicker frequency does not depend appreciably upon the wave-shape of flicker, that is, upon the manner in which the illumination varies in passing between the maximum and minimum cyclic values." As the apparatus diagrammatically shown in Fig. 1 readily lent itself to a study of this problem some experiments were carried out in order to determine whether wave-form of flicker is sufficiently important to bear investigation in regard to its effect in flicker photometry. The experiments were made with clear tungsten light. It has been established by Porter[2] that $f = k \log I + p$ represents the relation between critical frequency, f, and the illumination, I, where k and p are constants. In Fig. 7 the writer's results obtained with flickering lights of different contours of flicker. In cases a, b, and c the maximum, minimum, and mean cyclic values of illumination were respectively the same. In case d, for a given mean cyclic illumination the maximum illumination was 4.5 times that in cases a, b and c. The mean illumination on the photometer screen in meter candles is plotted logarithmically. Similar to what was found by Porter one straight line relation is seen to hold down to a low illumination where another straight line relation seems to begin. The location of this point of course depends upon the absorption of light in the photometer used and in these cases seems to depend somewhat upon the contour of flicker although the points where the lines of lesser slope begin are not well defined. The data shows that critical frequency varies even with equal values of maximum and minimum illumination. Further on comparing a, b and c it is seen that the contour of flicker determines the critical frequency. On comparing d with the other cases it is seen that the critical frequency at a given mean illumination is much higher when the period of darkness is greater or

[1] Proceedings of the National Elec. Light Assn., 1907.

[2] Proc. Roy. Soc., LXXIX., 1902, p. 313.

where the maximum value is greater. Further it is seen that the shorter the period of darkness the lower is the critical frequency at a given mean illumination when the maximum and minimum values of the flickering lights are the same. In other words the more abruptly does the stimulus rise in value the greater is the critical frequency. It is thus seen that the

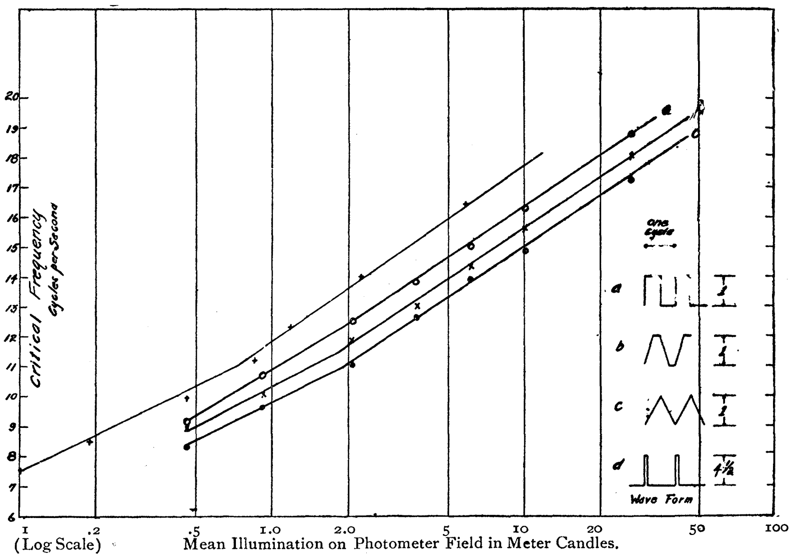

Fig. 7.

Effect of Wave-Form of Flickering Lights on Critical Frequency.

contour of flicker has a highly important bearing upon the critical frequency. These results contradict the statements quoted from Kenelly and Whiting. From these data it is seen that critical frequency is influenced by the contour of flicker, and the maximum, minimum and mean values of illumination during the cycle.

SUMMARY.

1. Red and blue-green lights add in the same manner whether by direct superposition or by alternately flickering them as in the flicker photometer when the speed is not lower than that at which flicker is barely apparent.

2. The maximum value of a flickering red light is always greater than that of a blue-green light flickering in the same manner and at the same frequency, when the steady values of the intensities of these two lights are those determined by a direct comparison balance. This is very much more marked when a red light is flickered upon a steady blue-green field than when a blue-green light is flickered upon a steady red field. In the latter case the agitation of the field which consists of a red light flickering

upon a steady blue-green field is much more marked than in the opposite case at practically all speeds below the critical-frequency speed. This seems to account for weighting red light more than blue-green light by the flicker method than by the direct comparison method.

3. The speed at which flicker disappears is much higher for the red light in the foregoing cases just noted than for blue-green light of the same intensity as determined by comparing the two lights by the direct comparison method.

4. It is shown that the contour of flicker has considerable influence upon the critical frequency which is the frequency at which flicker vanishes at a given illumination when the light is alternated with darkness.

The writer is indebted to Mr. Leonard Krill and Mr. Abe Shapero for assistance in the experimental work and Mr. H. MacMullen for the preparation for the drawings.

Appendix.

An interesting experiment the results of which point with favor to the flicker photometer is found in comparing lights of the same color but differing in spectral character. By means of dyes two yellow lights identical in color were produced. One was a pure yellow while the other was a subjective yellow composed of green and red light. These were balanced by the direct comparison method very readily because there was no color difference. When balanced by the flicker method it was found that the results were the same as obtained by the direct comparison balance within at least one per cent. The same experiment was performed with "white" lights, one being the continuous spectrum light from a tungsten lamp, the other being made by mixing red and blue-green lights. Here again the results were practically the same by the two methods. These experiments indicate quite strongly that the flicker photometer is not effected by the difference in the rates of growth and decay of color sensations. Of course other combinations of colored lights to produce two lights of the same color but differing in spectral character might give different results by the two methods. If no differences are found it might be fair to assume that the flicker photometer measures true brightness and that the differences in the results by two methods are entirely attributable to the effect of simultaneous contrast and other phenomena involved in the direct comparison method. The latter method does not satisfy the fundamental axioms already mentioned which is a serious cause for looking upon this method with disfavor when seeking a reliable method of photometry for the standardization laboratory. In summing up the evidence it appears that for a laboratory method the balance is in favor of the flicker photometer.