A PRECISION ARTIFICIAL EYE.

By Herbert E. Ives.

The most attractive solution of all problems of measurement which depend upon the characteristics of a normal or average eye is to embody these characteristics in some entirely physical instrument. Among these problems may be mentioned as most important the measurement of luminosities of lights of different color, and the measurement of color. In each of these cases the value obtained by a single observer, by whatever method employed, is apt to be of little value. Numerous observers must be called upon in order to secure an average value. If, however, the properties of the average eye can be reproduced in an artificial physical eye this troublesome and often impracticable procedure may be avoided.

In a recent paper[1] a thermopile artificial eye was described, consisting of a sensitive thermopile over which is placed an absorbing solution whose transmission copies quite closely the spectral luminosity curve of the average eye. One objection which might be raised to this instrument where absolute precision is in question, is that the "luminosity curve solution" must necessarily be merely an approximation to the experimentally determined luminosity curves, and therefore not applicable to all kinds of colors. Furthermore, if it is desired to copy more than one curve, as would be the case if color measurement on the three-color basis were attempted, the labor of working out the numerous absorbing solutions may be expected to be well nigh prohibitive.

The present paper describes a thermopile artificial eye that is not open to these objections. It is a precision instrument in the sense that any wave-length sensibility curve may be exactly copied. Once the instrument is constructed the labor of copying additional curves of any type is comparatively trivial.

The apparatus is a modification of the "Apparatus for the Spectroscopic Synthesis of Color," described some time ago.[2] It consists essentially of a spectrometer forming a spectrum which is passed through a template and then recombined upon a sensitive thermojunction. By means of templates of various shapes the radiation may be evaluated in any desired way, as luminous flux, as red, green, or blue sensation, etc. The possibility of doing this was discussed by Strache,[3] in his proposal to establish the standard of light radiometrically, but to the best of my knowledge has never been tried experimentally, probably owing to the lack of sufficiently sensitive means for the measurement of the small amounts of radiant power involved.

Fig. 1 exhibits diagrammatically the complete apparatus. The image of a filament or extended light source L is formed on the slit S by means of a lens. A spectrum of this is formed by the prism P at S^1. Over this spectrum is a template, which may be in the form of a rotating disc, or which may be a flat stationary plate, as will be discussed presently. Close

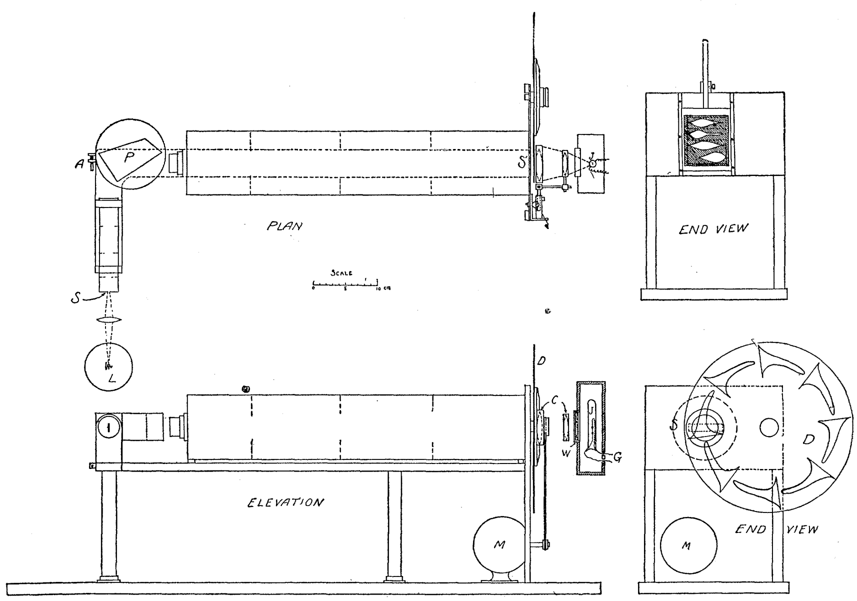

Fig. 1.

Diagram of the precision artificial eye. L, light source; S, slit; P, prism; S', spectrum; D, disc template; C, condensing lenses; W, tank for absorbing solution; J, thermopile; G, galvanometer lead; M, (clock or hand) motor; A, adjusting screw for prism table.

to the template is a lens or lens system, whose function is to recombine the spectrum, forming an image of the prism face in the color of the recombined light upon the thermojunction J. Further details of the apparatus will be described in the discussion of their functions. Detailed information on the method of calculating the openings of the templates, etc., is to be found in the paper previously referred to.[2]

By far the most important point to be determined in connection with the development of such an instrument is whether adequate sensibility can be obtained. The degree of sensibility required is very high. The radiation to be measured lies of course entirely in the visible portions of the spectrum, a region of very low emission in all the artificial light sources which would be the subject of measurement. Moreover the intrinsic brilliancy, which is a definite limit to the amount of energy which may be received through a dispersing apparatus, is with many light sources quite low. These points are illustrated by noting that radiometric studies of the visible spectrum have been few, chiefly confined to light sources of high intrinsic brilliancy like the Nernst glower or incandescent electric lamps. These have intrinsic brilliancies of the order of magnitude of 100 or more candle power per square centimeter, while the glass mercury arc or the Welsbach mantle (in the study of which this instrument is to find its immediate use) drop below 5 of the same units.[4]

A detailed study of the factors conditioning sensibility brings out several points of interest. For a light source of given intrinsic brilliancy it is obvious that the amount of energy focused on the thermojunction is directly proportional to the width of slit employed (it being understood that the entire slit width is filled with the image of the light source). It is also directly proportional to the angular extent of the telescope lens as viewed from the point of formation of the spectrum. It is directly proportional to the vertical height of the spectrum utilizable. It is of course dependent also upon the number of reflecting and absorbing media used in the prism and lens system.

Assuming that the spectrometer system has been so designed that a spectrum is formed (of sufficient length to be practically handled by a mechanically cut template), using the maximum width of slit permitted by the purity necessary, of maximum feasible telescope aperture, as conditioned by the necessary degree of definition; utilizing the greatest vertical length of spectrum, as conditioned by the curvature of the slit image and the length of the slit image which is of uniform brightness; and possessing the minimum number of light obstructing surfaces,—the rest of the problem is that of attainable radiometric sensibility.

Probably the most sensitive means for measuring radiation, suitable for the present problem, is furnished by the thermopile with appropriate galvanometer. Using this combination the problem of sensibility consists of two parts, the thermopile problem and the galvanometer problem.

The thermopile problem is of particular interest, for this reason; that with the optical arrangement assumed the attainable sensibility is limited practically to the intrinsic sensibility of a single junction. This is made clear by considering first the recombined spectrum as entirely received upon a single junction. Suppose now it is desired to use *n* junctions; the image of the prism face would have to be n times larger, each junction would receive $1/n$ times as much radiation; in other words the thermoelectromotive force developed would be the same. If the resistance of the n junctions is the same as that of one junction the current developed will be the same in the two cases. The only possible gain in the use of many junctions therefore lies apparently in the decreased resistance which might be obtained by joining the junctions in parallel. The resistance of a single junction is however so low in comparison with that of the galvanometer that no great gain in sensibility may be expected by the use of multiple junction piles.

This limited condition naturally directs attention to means for securing the maximum intrinsic sensitiveness of a thermojunction. In the present case use is made of a BiSn-BiSb thermojunction of the evacuated type, constructed by Dr. E. Karrer in general conformity with the design published by Dr. A. H. Pfund.[5] This junction, of alloys having a higher thermoelectric power than any pure metals commonly used, is increased in sensibility five to six times by the process of exhausting the containing vessel. It is equivalent to ten or twelve bismuth-silver junctions. The actual junction used has for receiver a tin plate approximately two millimeters square. The image of the prism face, formed by a system of three achromatic lenses, is of closely the same area, but being round projects a little beyond the junction at each side. Obvious improvements would be to furnish the junction with a round receiving plate, to secure the equivalent lens system with fewer glass surfaces, and if possible reduce the size of the prism image, since the sensibility of a junction only increases with the square root of the area. With all these changes made however it is doubtful whether the sensibility could be more than doubled; hence the use of the vacuum junction gives at least five times the sensibility to be expected from any other form now available. This factor, in the apparatus constructed, just makes the difference between adequate and inadequate sensibility.

The galvanometer employed is an iron-clad Thomson instrument designed by Coblentz. Its resistance is 5.1 ohms. Its sensibility as ordinarily used by us is from 2 to 5×10^{-10}. amperes per mm. deflection, with a period of three to six seconds. The galvanometer is enclosed in a series of soft iron pipe shields, to protect from magnetic disturbances (with which we are not however much troubled in our laboratory), and is carried on a Julius suspension to protect it from mechanical vibration. This latter is a very serious problem with us, as a 20-inch gas main direct from the near-by gas pumping station makes a right angle turn only thirty feet from the laboratory. Every throb of the pump was reflected in a centimeter jerk of the galvanometer when this was mounted merely upon a heavy pier. The Julius suspension, constructed closely in accordance with the original publication of Julius,[6] entirely eliminated this trouble. The control magnets are mounted partly on the suspension (which is locked to a surrounding ring when these are being adjusted) and partly on the top of the shielding system. The latter magnets are used almost solely for turning the mirror to bring it in the proper part of the scale. The whole system—galvanometer, shields, etc.,—is mounted inside an enclosing box which prevents air drafts from starting long period swinging. These details are mentioned in order to show that the apparatus, although possessing high sensibility, is not impractical in form for the average laboratory, where conditions should be much better than in our own.

The first template tried was in the rotating disc form, shown in the figure at *D*. This was cut to the visual luminosity curve as recently fixed upon by work reported in this journal,[1] correcting for the absorption of the prism, shown in Fig. 2. Using a carbon lamp as the light

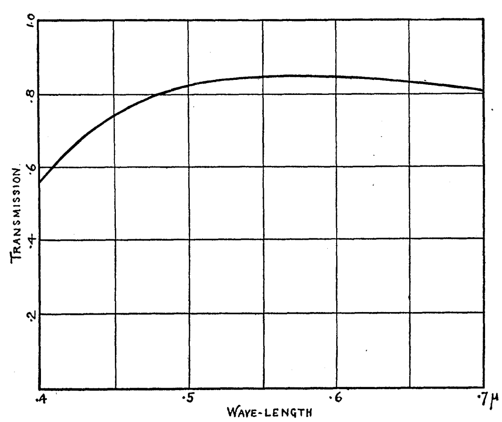

Fig. 2.

Spectral transmission of prism used in precision artificial eye. (Measurements made on block of identical glass supplied by makers of prism. Thickness 9 cm.—that of light path through prism—refractive index 1.6181.)

source, and a slit width of about 50 A.U. in the green, deflections of five or six centimeters were obtained, demonstrating the feasibility of the scheme.

It had been anticipated, however, that one of the practical difficulties would be the presence of scattered radiation, due to the hundred-fold greater amount of invisible than visible radiation. It was thought to eliminate this in part by the use of a water tank *W* before the thermojunction, but it was soon suspected that some still remained. A test experiment verified this suspicion. A solution of iodine in carbon disulfid was prepared of such concentration that only the deep red and violet were transmitted. The red and violet ends of the spectrum formed at S^1 were covered with opaque screens, and the light exposed. A deflection of about ten per cent. that previously found was now obtained. This amount of scattered radiation in spite of the presence of the water tank, and the great length of the spectrometer system, appears to the writer to cast considerable doubt on the accuracy of data on the visible end of spectral energy distribution curves obtained without the use of most elaborate means for eliminating such errors.[7]

To remove the disturbing infra-red radiation recourse was made to a screen of copper chloride, in place of the water at *W*. A three per cent. solution of one centimeter thickness was found best suited to meet all requirements. When using this screen of course the template transmissions must all be increased by the reciprocal of the transmission of the copper chloride. This involves the exact determination of this transmission by the spectrophotometer, whereby an undesirable but apparently unavoidable element of uncertainty is introduced. The necessity for uniform temperature also enters owing to the temperature coefficient of transmission of the copper chloride. It is possible that a copper glass would serve in place of the solution and be free from the last objection, which however is not at present serious.

As the labor of cutting the disc template is considerable it was decided to make the new curve in a fixed form. This is possible in the present arrangement where it was not in the original synthetic color apparatus[2] because in the latter the eye was used at the observing slit, and the aperture of the eye imposed an impractical limitation to the possible slit length. Where it is possible to cast upon the slit *S* a long uniform image, such as that from an incandescent lamp filament, the use of a fixed template is much the simplest scheme. It is only necessary to be sure that the whole width of the spectrum used receives light from the whole of the prism face, which may be tested by moving the eye up and down the vertical length of the spectrum. An advantage of the fixed template is that no motor is necessary. The latter, by the way, must in working near a sensitive galvanometer, be clock or hand driven.

To cut the new templates a photographic method was employed. The curves desired were calculated and then laid out on a large scale with drawing instruments. The parts desired opaque were painted black, and the reference wave-length line (.5461) clearly marked at the ends of the sheet. This was photographed down to the correct size and the negative, which was made thin, was painted in the exposed parts with opaque pigment. From this a thin print on glass was made which was in turn painted with opaque paint by carefully following the edges of the exposed portions. By taking such precautions as printing in a printing frame with a black velvet back, and not carrying the development far it is possible in this way to secure beautifully clear and (with ordinary draftman's skill in the painting) accurate templates. Fig. 3 shows the

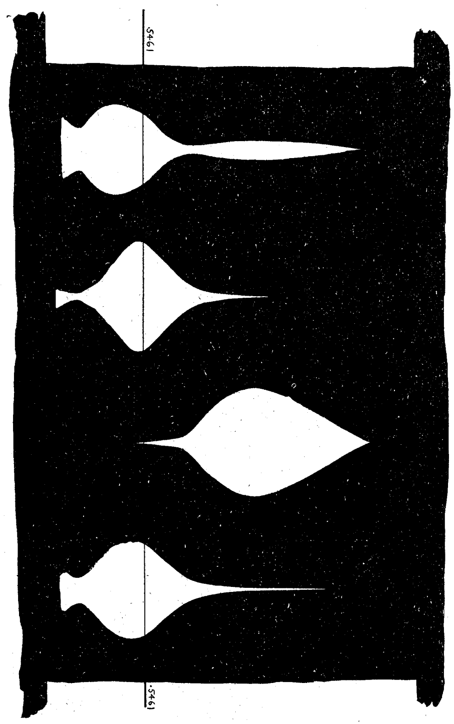

Fig. 3.

Drawing for stationary template. Top, luminosity curve. In order, blue, green and red sensation curves.

template so constructed. It has upon it the luminosity curve of the spectrum, and the red, green and blue Koenig sensation curves. The peculiar spreading at the red end is called for to offset the absorption of the copper chloride.

This glass template was mounted with adjustable clamps upon a brass frame sliding in accurate tracks, as shown in the figure (the upper "end view"). Tests of this arrangement showed entire absence of scattered radiation. It was then tried out on the same test colors used in the work on the thermopile artificial eye previously described.[1] With the standard carbon lamp it was found possible to obtain deflections of 20 centimeters and over (workable deflections were obtained with a Cooper-Hewitt mercury arc), but more satisfactory results were given by keeping the deflections down to three or four centimeters by the introduction of extra resistance in the galvanometer circuit. Measurements made on the test colors showed very satisfactory agreement with the visual values.

In addition to the measurement of relative luminosities this instrument may be used for color measurement by the three-color system. It is only necessary to have three templates each cut to represent the mixing proportions throughout the spectrum of one of the chosen primaries and measure the relative deflections through these. The logical primaries to choose are the fundamental sensations, for instance as determined by Koenig.[8] (Measurements in terms of these may be transformed into the values obtained by using other primaries or into hue, luminosity and purity values.) These curves have been reproduced in the glass template shown in the figure, the energy distribution of a black body at 5,000° abs. being taken as "white," and have been tried out for actual color measurement.

A 3.1 w.p.c. carbon lamp was measured, the values for the three sensations coming out:

$$R = 50,$$
$$G = 43,$$
$$V = 7.$$

Values which I calculated some years ago,[9] on an assumed distribution of energy for the carbon lamp were:

$$R = 51,$$
$$G = 41,$$
$$V = 8.$$

It will be seen that these values are reasonably close to each other. There is at present no criterion by which to decide that the measured values are not the correct ones. This measurement of color is intended to be merely illustrative. A table of values on artificial illuminants may later be compiled and published.

Certain refinements are suggested on this first apparatus. For instance, the possibility of scattered light affecting the results could be met by covering each template opeining with a colored glass approximating the curve desired, letting the shape of the opening merely take up the difference between the glass transmission and the true curve. Thus a thin sheet of gold ruby for the red, a sheet of "pot" green glass for the green, a piece of "signal blue," for the blue would admirably meet the requirements. In each case of course the spectral transmissions of the glasses would have to be accurately determined.

Now as to the uses of this precision artificial eye. First its uses in photometry. Here its chief application will be in the measurement of the transmissions of colored absorbing media to be used in eliminating color differences upon the photometer. With templates cut, as has been explained, exactly to a legalized luminosity curve of the spectrum, an instrument of this type is calculated to become a standard artificial eye, suitable for the foremost standardizing laboratories.

Second, its uses in color measurement. Here its chief application will lie in the measurement of the colors of illuminants. The general loose descriptions of lights as "snow white," etc., can be superseded by exact evaluation in definitely established units, which may be made without dependence upon the visual characteristics of a chance observer, or the necessity for comparison with a concrete color standard. The colors of glasses or other transmitting media may be determined with this instrument. These may be measured over some convenient light source, such as a carbon lamp, or if desired the templates may be so cut that while actually using a source of known energy distribution quite different from white light the results are in terms of the white light transmissions. In order to do this it is only necessary to determine with accuracy the spectral energy distribution of some convenient light sources in the visible region, a task of some delicacy but nearer practicability now than formerly.

As an illustration of a technical application of the device may be suggested the inspection of colored glass such as "daylight glass." Having determined what a correct sample (as fixed by the use of this same instrument as a synthetic color producer)[2] should measure when interposed over any convenient reproducible standard light source this value could be plotted on a color triangle, and to establish a tolerance limit a circle of size to be agreed upon by the parties interested could be drawn from this point as center. The sum of the three measured values would afford a check on any admixture of black which might decrease transmission without altering the color. Or a measurement of total transmission could also be made with the luminosity template. By this means the measurement or inspection of colored glasses could be made an exact problem. (A similar scheme giving results in entirely arbitrary units could be worked out, using three color-screens of overlapping transmissions. The instrumental sensibility required for this scheme would be far less than for the precision device.)

The description of the instrument as constructed is given here chiefly to show that such a device is actually feasible, with the instrumental means now at the disposal of the physicist. It is limited in its application to those cases where a relatively large amount of light is available, as has been indicated, but these cases are sufficiently numerous to offer a large field of usefulness. It is to be confidently hoped that the near future will disclose means for considerably increasing the sensibility, perhaps by as much as five or ten times. It is to be expected that a detailed study of the present instrument will show possibilities for considerable improvement even with present radiometers. Such improvement as increased aperture and reduction of the number of reflecting surfaces would help materially. The thermopile can undoubtedly be somewhat better calculated for its purpose, by making the receiver round, and perhaps under some conditions by a parallel connection of

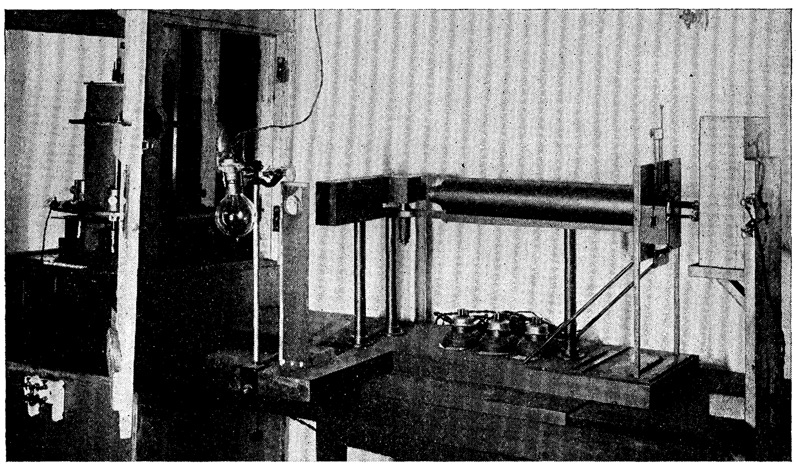

Fig. 4.
Photograph of precision artificial eye.

several junctions. There is besides the possibility that some more sensitive thermojunction will be developed (for instance bismuth-tellurium) which would be entirely satisfactory as a vacuum instrument for use with visible radiation only, restrictions which while serious in some work would not be at all so for this purpose. Could the wave-length sensibility curves of sensitized photo-electric cells[10] be controlled another form of radiometer might be utilized. Whatever may be the development of the future the writer wishes to emphasize that the first step has been taken, a precision artificial eye has been constructed and is in use.

I take pleasure in acknowledging my indebtedness to Mr. E. J. Brady, Mr. E. F. Kingsbury and Dr. E. Karrer, who have cooperated with me at one stage or another in the development of the instrument. Special acknowledgement is also due to Mr. Charles B. Smith, whose mechanical skill and practical suggestions contributed substantially to the success of the work.

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PHILADELPHIA, PA.
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[2] "An Apparatus for the Spectroscopic Synthesis of Color," Ives and Brady, Journal of the Franklin Institute, July, 1914, p. 89.

[3] Strache, Proc. American Gas Institute, 2, 401, 1911.

[4] "Measurements of Intrinsic Brightness by a New Method," Ives and Luckiesh, Electrical World, Feb. 16, 1911, p. 438.

[5] "A Sensitive Black-Body Vacuum Thermojunction," A. H. Pfund, PHYS. REV., XXXIV., p. 228, 1912.

[6] Julius, Annalen der Physik, 56, p. 151, 1895.

[7] R. A. Houstoun (Proc. Roy. Soc. Edin., Vol. XXXI., 4, No. 36, 1911), in agreement with this observation, found it necessary to adopt elaborate precautions to eliminate stray radiation when working in the regions of low emission.

[8] "Die Grundempfindungen," etc., A. Koenig and C. Dieterici, Zeits. für Psychologie u. Physiologie, 4, p. 241, 1892.

[9] "Color Measurements of Illuminants," Ives, Trans. Illuminating Engineering Society, April, 1910, p. 189.

[10] "Wave-length Sensibility Curves of Potassium Photoelectric Cells," Ives, Astrophysical Journal, Vol. XL., No. 2, Sept., 1914, p. 182.

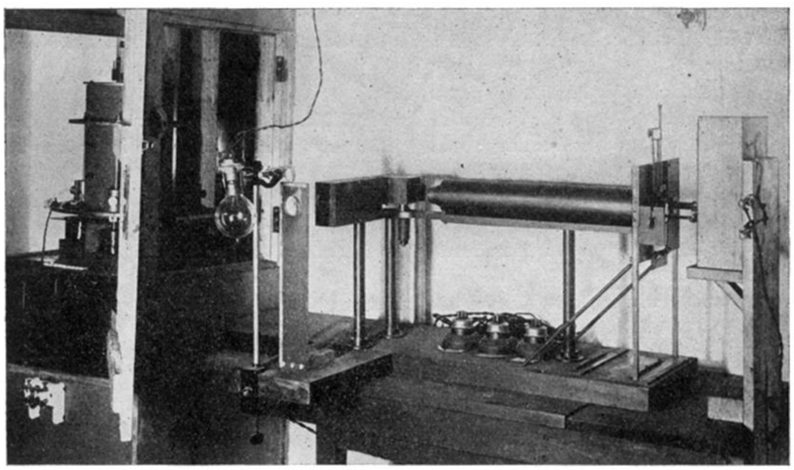

Fig. 4.
Photograph of precision artificial eye.