SENSITOMETRY SINCE HURTER AND DRIFFIELD*

By DR. S. O. RAWLING

THE best memorial to Hurter and Driffield is the continued application of their teaching by the photographic industry. The basis of photographic sensitometry is a characteristic curve of the material under test, and when we remember that the particular characteristic curve in use to-day is still known as the 'H and D curve', obtained by plotting density against the logarithm of the exposure, we realize the excellence of the work which was done so long ago by those two enthusiastic amateurs. The principle of sensitometry remains what it was when Hurter and Driffield left it. The details have changed; the values of the co-ordinates of the curve have been corrected and brought nearer to standardization; new apparatus has been applied to the work and the results themselves are interpreted in new ways which make it possible to link sensitometry much more closely with practical photography. I propose to sketch in outline some of the ways in which the H and D curve has been pulled into shape in order the better to guide those who use photography and those who must provide the best kind of photographic material for each particular purpose.

It is almost fifty-three years since Hurter and Driffield published what was probably the most important of their papers[1]. This was entitled "Photochemical Investigations and a New Method of Determination of the Sensitiveness of Photographic Plates" (*J. Soc. Chem. Ind.*, May 31, 1890). In this paper they described shortly the "laws of absorption of light by opaque black substances" and defined the meaning which they attached to the terms opacity, transparency and density of a negative. They stated their opinion that "a negative is theoretically perfect when the amount of light transmitted through its various gradations is in inverse ratio to that which the corresponding parts of the original subject sent out". They described a photometer for measuring density and went on to report on the behaviour of photographic plates, using this instrument for measuring the response of the plates to exposure and development. The general shape of characteristic curves was demonstrated, and from this they put forward their doctrine of how to obtain negatives which by their definition should be perfect. Lastly, they described a method of calculating photographic speed values from characteristic curves.

My argument will be found to arrange itself quite naturally about the H and D curve. To begin with the density axis, there came early difficulty. The first note of 'trouble' was sounded in 1891 by Hurter and Driffield themselves in a paper[2] on the "Relation between Negatives and their Positives". Using density values determined on their own photometer, they found that the effects of exposures to light behind the negatives were greater than those calculated directly from the densities as measured. They supposed that this was caused by light reflected from the surface of the printing material, and that part of this light was then reflected back again by the negative on to the printing material. They summarized their observations thus: "The coefficient a which converts the density as measured, into the printing density, is, for negatives developed by ferrous oxalate, usually a fraction; for pyro developed negatives it is generally nearly 1, if the negatives be used for contact printing; but when the negative is used for enlarging the factor a . . . is always greater than 1, even for negatives developed with ferrous oxalate".

Some values of a found for contact printing were 0·8, 0·665, 0·577. The principal cause of the wide disparity between these values of a and unity was, however, not 'inter-reflection' of light in the printing process, but the unaccounted loss of light by scatter from the negative in their photometer.

Abney directed their attention to the scattering power of negatives, and tried to show that their photometer might not be giving the true optical density. A lively argument followed, from which Hurter and Driffield emerged at last admitting that "the Captain is not yet satisfied that our photometer gives the true optical density" and adding that "density, however expressed, will need different corrections for different operations". Even in this incident we must admit the prophetic nature of their last remark, which was the expression of a truth not always appreciated at the present time.

Abney was right about the scattering of light. The error caused by inter-reflection was small compared with that caused by scatter. Hurter and Driffield's photometer employed direct beams of light between two lamps and a grease-spot photometer, the negative being inserted in one of the beams. Some of the light transmitted by the negative was scattered out of the direct path and never reached the grease-spot. Thus the instrument recorded density values which were too high.

By integrating the whole of the light transmitted by the negative, density values closely approaching contact printing densities are obtained. In general practice, a sheet of white opal glass in contact with the negative serves very well as an integrator, and most of the densitometers now in use employ this device.

Density measurement has not yet been standardized, though with well-designed contact opal densitometers it is possible to compare results obtained in various laboratories without finding serious discrepancies. The comparison is, of course, limited to contact printing technique, and if negatives are to be used in any other way the original caution of Hurter and Driffield must be taken into account: "density . . . will need different corrections for different operations".

The movement towards standardization of sensitometric technique has been most marked in the establishment of standard light sources for sensitometers. The candle and other flame sources have become obsolete, and in their places are electric lamps run at specified colour temperatures.

The commonly used, substandard, vacuum lamp of the photometry laboratories is capable of working well at a colour temperature of 2,360° on the Kelvin scale of temperature, and it was finally decided that such a lamp should be adopted as part of the standard light source for photography. The choice of 2360° K. appears to have followed from the fact that this was supposed to be the colour temperature of the acetylene flame, which had been used with a correcting filter to imitate sunlight.

The 2360° K. light was, however, not adopted as a complete standard. It was capable of much higher output than the candle and it was relatively richer

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* Substance of the Hurter and Driffield Memorial Lecture of the Royal Photographic Society, delivered on November 28. The lecture is being published in full in the *Photographic Journal*.

in blue light, but photographic technicians craved for a more evenly balanced distribution of energy such as occurs in direct sunlight. The improvement demanded was not to be gained without sacrifice. It was necessary to filter out the excess of green and red light. The experience of the standardizing laboratories was used in selecting the suitable filter, and after a considerable amount of argument the choice was made from a large series of filters devised and specified by Davis and Gibson[3], of the American Bureau of Standards. This filter converts light from a colour temperature of 2360° K. to the approximate quality of mean noon sunlight at Washington. Thus we are in possession of the specification of a standard light source which can be realized very easily in the laboratory, which gives a fairly even distribution of energy over most of the visible part of the spectrum, and satisfies those who cry for 'artificial sunlight'. In passing, it may be noted that the extreme variations in the quality of real daylight are probably almost as great as between ordinary electric light and mean noon sunlight. For example, the light from clear blue sky is almost as weak in red as the electric light is weak in blue. Nevertheless, the compromise adopted for laboratory work must be considered as a very reasonable one.

Recently there has been found a need for light sources of very much higher power. The substandard photometric lamps are vacuum lamps and cannot be run at temperatures much above 2360° K., and their total candle-power is in the neighbourhood of 30. The invention of the gas-filled lamp has provided lamps which can be run for long periods at a temperature of about 2850° K. without much change in output. It is quite common to develop several hundred candle-power in a single small lamp of this kind, and there is available another Davis and Gibson filter which converts 2848° K. (say, 2850° K.) to mean noon sunlight. This filter, since it has not such a wide gap of colour temperature to bridge, has a considerably higher transmission ; thus the resulting laboratory sample of mean noon sunlight is of far higher available candle-power than that of the 2360° K. source with its appropriate filter.

The establishment of a standard light source has been one of the most valuable results of all the efforts which have been made towards standardization of sensitometric methods. It is, however, far from being the only factor controlling the abscissæ values of the characteristic curve. Exposure, being a product of time and intensity, introduces the question of which of the factors is to be varied in giving the series of test exposures necessary for determining the characteristic curve of the material under test. Hurter and Driffield, probably for convenience, varied time, keeping intensity constant ; we now call this a 'time scale' method. They assumed that the results would have been the same if time had been kept constant and the intensity had been varied. But reciprocal variation of time and intensity does not always produce equivalent photographic results. In pictorial photography the varying tones in a given negative are all produced by exposure for the same time (determined by the shutter) to a series of intensities determined by the brightness of the various parts of the image in the camera. It seems, therefore, that the ideal system would be to use an intensity scale in sensitometry. This, however, is easier said than done. On the other hand, time-scale sensitometers are easy to specify and can be constructed with great precision. They have accordingly found great favour in certain applications ; for example, they are admirable in providing a scale of exposures for the test negatives employed for checking the performance of developers and developing machines ; they are also excellent for checking the uniformity of production of photographic materials. Their main limitation is that they do not give reliable information about the performance of different materials in the camera. The trend has therefore been, in studying the behaviour of different materials in practice, to use so far as possible intensity-scale sensitometers at times of exposure comparable with those employed in the camera.

There are two main difficulties in devising a sensitometer to work on the intensity scale principle. The first of these is the enormous waste of light in providing a wide scale of intensity. The unmodulated light must be of high power in order that the lowest intensity of the scale shall be adequate. It is not uncommon for the last step of a sample exposed in a sensitometer of this type to receive less than one thousandth part of the light received by the first. The second difficulty is that of providing means for varying the intensity over a sufficient range without introducing some change in the quality of the light. The common way of referring to this is to say that it is difficult to make a *neutral* intensity modulator. The common gelatin wedges devised by Goldberg[4] were made of such materials as India ink mixed with bluish dyes to give a reasonable approximation to visual neutrality. They were, however, more heavily absorbing in the blue, violet and near ultra-violet, and more transparent to red and infra-red, than in other regions of the spectrum, and, when employed without proper consideration for this fact, have led to some very misleading conclusions. Other materials, such as highly dispersed graphite and developed emulsion, have been used for casting wedges, but no very satisfactory material for casting really neutral wedges has yet been made available. Stepped wedges can, however, be made by exposing photographic plates in stepwise manner and then developing them. Such wedges are usually sufficiently neutral for ordinary sensitometry.

We have now come to the interpretation of results of sensitometric measurements. Hurter and Driffield considered the photographic speed of a negative material in terms of the minimum exposure necessary to record the deepest black of a scene on the lower extremity of the straight line region of the characteristic curve. It is true that their graphical method of determining speed necessarily implied the inclusion of a little of the foot of the characteristic curve where the slope is changing and is less than that of the straight line, but with the negative materials which they favoured the amount of the foot so included was small, and we must admit that these negatives conformed very closely to *their definition* of a perfect negative if we ignore, as they did, the distortion of tone produced in the image by scattered light within the lens and camera.

One conclusion which has been drawn from the theory of tone reproduction is that, for true tone reproduction *in the print* made from a negative, the product of the slopes of negative curve and positive curve should be unity. Now in making prints on paper it is, more often than not, desirable to use almost the whole tone range of the paper from nearly clear white to a density approaching the maximum black possible. Thus the whole of the characteristic curve of the paper comes into play, and since this curve really is 'curved' and not a straight line for the whole of its course, a complication of the Hurter and Driffield doctrine results. To obtain a perfect print, the angle of slope of each part of the negative curve must be complementary to that of the corresponding part of the paper curve. The highlights of the scene correspond with the darkest part of the negative and with the lightest parts of the print which are recorded on the least sloping part of the characteristic curve of the paper. The negative record of this part of the scene should therefore be on the most steeply sloping parts of the negative curve. At the other end of the brightness scale of the scene the deepest shadows are recorded near the deepest black of the paper where the slope of the paper curve is greatest. This part of the scene will be recorded at a lower density region of the negative curve, and it follows that the slope of this part ought to be lower than of that part of the curve corresponding with the highlights. Thus the negative should include part of what Hurter and Driffield called the under-exposure region of the curve.

The problem is to decide how much of the lower part of the negative curve should be included. As an experimental argument, let us try whether the question may be answered by selecting as a limit that point on the negative curve where the angle of slope is the exact complement of the slope of the paper curve in the region which is to depict the shadows of the scene. With a very large proportion of present-day printing papers, the region of the characteristic curve used for the greater part of the shadows is that of maximum slope ; and this is generally related, roughly at any rate, directly with the contrast-giving power of the paper. By using the 'hardest' printing paper available, it will be possible to creep down a very long way into the foot of the negative curve and still obtain true tone reproduction in the deep shadow regions of the print. Meanwhile, however, what has happened to the remainder of the tone scale ? The choice of the hardest available printing paper will bring with it the difficulty that the whole tone scale of the paper will be brought into action by a very small density range in the negative, and our print, while recording the deepest shadows with accuracy, may exaggerate the middle tone differences and record all the highlights as blank white paper. Thus the limit of our creep down the negative curve in search of speed must be set not only by the conditions necessary for reproducing shadow detail but also by the total density range of the negative. The latter is the main factor which determines the contrast grade of the paper which must be used in printing, a fact very well understood by Hurter and Driffield themselves. The contrast grade of a printing paper may indeed be fairly accurately expressed in terms of the negative density range which it will accommodate[5].

The slope of the curve of the selected printing paper must therefore depend on the density range of the negative from which the print is to be made. The smaller the density range of the negative, the greater must be the slope of the paper curve and vice versa. Our first attempt at deciding how far we may creep into the 'under-exposure' region of the curve has thus failed, unless we first choose a printing paper of the correct exposure range (correct contrast grade) for the negative concerned.

Photographic 'speed' of a negative material thus appears to depend not only on the power to record shadow detail, but also on the density range produced in the negative by the whole scene, that is to say, upon the contrast of the negative as a whole.

As a rule, the main pictorial interest of a photograph does not lie in the extremes of the tone-range but somewhere near the middle, and we are generally satisfied with a print in which extreme shadows are lacking in a little of their detail. That is to say, instead of insisting on perfect tone reproduction in the shadows, we can there accept some compression of the tone-scale, and the product of the slopes of the negative and positive curves can be less than unity.

We must, however, satisfy the general condition that the density-range of the negative and the contrast grade of the paper must be suited to one another. L. A. Jones has, during the past few years, made a thorough investigation of this problem, and has suggested as a criterion of speed for ordinary pictorial negative materials the exposure corresponding with that point on the characteristic curve where the gradient is 0·3 of the average gradient for a negative recording an image brightness-range of 32.

Jones[6] has tested this criterion by a statistical method. He prepared a number of transparencies of landscapes to serve as laboratory originals for his experiments. His use of one of these transparencies will serve to explain his method. A series of negatives having progressive increase of exposure was made upon each of a number of negative materials. From each negative the best possible print was made, using for each the most suitable available grade of printing paper. Thus for each negative a series of prints was obtained. The quality of these prints varied from quite unacceptable through just acceptable to excellent. Jones employed a group of about two hundred observers to answer the question : which, in the series of prints arranged in order of increasing negative exposure, was the first one which could be called excellent ? The majority vote was taken for each series and so the minimum camera exposure necessary to yield *the first excellent print* was established for each negative material. This was eventually done for more than seventy negative materials and for several scenes, and made it possible to establish the relative working speeds of the materials as judged on pictorial results by the average observer. These results were then used as the established yard stick with which sensitometric determinations of speed could be compared.

The comparison between the statistical practical estimate of speed as determined by the selection of the first excellent print and the speed as measured by the fractional gradient method gave a total spread of 0·17 on the logarithmic scale. That is to say, taking the extremes, two films which are really alike in speed would be judged to have speed values not more erroneous than by a factor of antilog 0·17, that is, 1·5, if their speeds were calculated by the sensitometric method. This criterion is still 'under observation' by various standardizing committees.

I began with some discussion about the influence of scattered light upon the value of density. I end by directing attention to the influence of the camera and its lens in scattering light all over the image formed on the negative material. This light is often much stronger than is commonly supposed. It has the effect of distorting the brightness scale of the image in relation to the brightness scale of the scene. It was ignored by Hurter and Driffield, but has been discussed and investigated by various workers, of whom I should mention Goldberg[4] and more recently Jones[7].

This sketch cannot claim to be a full historical record of the progress of sensitometry since 1890, but I believe that it indicates the principal lines of progress, and provides the necessary starting points from which a student may go on to study in greater detail the science of photographic sensitometry.

[1] Hurter and Driffield, *J. Soc. Chem. Ind.*, **9**, 455 (1890). H. and D. Memorial Vol., p. 76.

[2] Hurter and Driffield, *J. Soc. Chem. Ind.*, **10**, 100 (1891). H. and D. Memorial Vol., p. 163.

[3] Davis and Gibson, *Mis. Pub.* No. 114, Bureau of Standards, Washington, D.C.

[4] Goldberg, "The Formation of the Photographic Image" (French edition, Paul Montel, Paris).

[5] Chilton, *Phot. J.*, **82**, 151 (1942). Romer and Rajski, *Phot. J.*, **82**, 66 (1942).

[6] Jones and Nelson, *J. Opt. Soc. Amer.*, **80**, 93 (1940); *Phot. J.*, **80**, 152 (1940).

[7] Jones and Condit, *J. Opt. Soc. Amer.*, **31**, 651 (1941).

OBSERVATIONS ON THE PHYSIOLOGY OF COLOUR VISION

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THE recent article by Granit[1] stimulates further thoughts upon the mechanism of colour vision, and his results may perhaps be interpreted in a slightly different manner.

There seems to be little reason to doubt that the appreciation of colour, as distinct from light intensity, must depend upon the presence in the retina of at least two elements of unequal sensitivity to the various wave-lengths of the visible spectrum. Two possibilities are therefore open. The first is that if we assume colour vision to be entirely mediated by cones, and the current views upon the structure and behaviour of the fovea give support to this assumption, we must postulate two or more types of cone or of cone sensitivity and trust that further research may lead to their actual demonstration. As the position stands to-day, apart from the existence of coloured globules in the cones of certain birds and marsupials, and apart from the extraction of a pigment, or pigments, with three distinct absorption bands from the retinæ of certain snakes[2], there is no histological evidence which speaks unequivocally in favour of the presence of different cone types distributed in the retinæ of higher vertebrates or of man in such a way as to be consistent with the facts of colour vision. Theoretical curves, expressing the sensitivity of hypothetical cone types (blue, green and red receptors) to different regions of the spectrum, have been constructed[3], but in order that they should satisfy all the necessary conditions the curves have to be so nearly identical in form and position that it is difficult to believe that any neural mechanism could be so delicately adjusted as to be able to appreciate the subtle differences of cone sensitivity which these curves indicate.

The second possibility is that the elements required for colour vision are those which are known actually to exist in the retina, namely, the rods and the cones. Owing to the peculiar structure of the fovea, which is believed to be rod-free, and to the general, though not universal, absence of Purkinje shift from this area, nearly all theories of colour vision have been based on the first possibility and the alternative hypothesis has received but scant attention. Nevertheless, it has several points in its favour and, since there are certain facts which fit more aptly into such a scheme than into others, it may be well to reconsider the hypothesis.

The functional sensitivity of the rods is indicated by the scotopic ocular visibility curve[4]. Their actual sensitivity has probably been most accurately expressed by the scotopic retinal visibility curve in terms of quanta obtained by Ludvigh[5], which among other things makes allowance for the absorption by the eye media. The maximum sensitivity of the rods lies at about 500 mμ, and the curve shows remarkable resemblance to the absorption spectrum of visual purple. Although the curve is normally obtained under conditions in which large quantities of this substance are present in the rods, there is no reason for believing that the differential sensitivity of the rods to different wave-lengths would change under daylight conditions when most, but probably not all, of the visual purple has been bleached. Indeed, Granit[1] has adduced evidence to show that, at any rate in guinea pigs, the rods do function in daylight and with the same differential sensitivity. Dark adaptation and the power to accumulate large quantities of visual purple in the rods may well be a secondary specialization of a more fundamental rod activity.

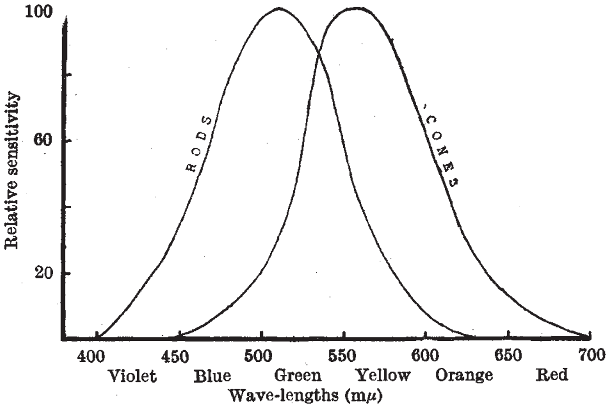

Fig. 1. SCOTOPIC AND PHOTOPIC VISIBILITY CURVES (EQUAL ENERGY SPECTRUM).

The functional sensitivity of the cones is probably closely represented by the photopic ocular visibility curve for the fovea obtained by Sloan[6]. Again, their actual sensitivity is seen in the photopic retinal visibility curve in terms of quanta recently obtained by Ludvigh[7]. The supposition that these curves represent cone activity receives direct support from Granit's observations in which the existence of a dominator is coincident with the presence of cones in the retina, and further support comes from the visibility curves for pure cone retinæ in which the maxima lie in the neighbourhood of 560 mμ. Recent determinations of this curve for the human eye by Ludvigh[7] show it to be remarkably symmetrical, a fact which he considers to favour the view that it represents either the absorption spectrum of a single substance or of a large number. He does not believe it to be consistent with the idea of three or four cone types such as would be required by the Young-Helmholtz theory in its popular form. Fig. 1, in which scotopic and photopic ocular visibility curves are plotted (equal energy spectrum), shows that the human retina in fact contains two elements which are differently sensitive to all regions of the spectrum and, if the