

THE PERSONAL ERROR IN PHOTOMETRY.

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Whenever, in the course of photometric work, different observers have occasion to compare the same pair of lamps, it will be found that the results of their readings with the Bunsen photometer differ by an amount very much larger than the apparent mean error of a single observation.

Ordinarily, these differences are cloaked by the accidental errors due to the fluctuations of the lights under observation, and they have, consequently, not received the attention which they merit. There has been, indeed, so far as I know, no systematic attempt to determine the precise nature and importance of this personal error, the existence of which has doubtless been recognized by very many observers.

The introduction of the storage battery and the adoption of the incandescent lamp, supplied from the constant source thus afforded, as a secondary standard, has, however, entirely removed the large accidental errors resulting from uncontrollable fluctuations in our standard of illumination, and the personal errors just alluded to accordingly stand out in their true importance. I have very recently had occasion to make some experiments upon this subject, the results of which may be of some interest to those who have occasion to work with the Bunsen photometer.

The character of the errors with which one meets continually, whenever the reading of two or more observers are brought into direct comparison, may be very well shown by means of two sets of readings made by Mr. B. W. Snow and myself, upon the same pair of lamps. These observations were made under precisely similar and uncommonly favorable conditions. The two lamps in question were of the same type, and being the only lamps in circuit with a large storage battery, they could be maintained at an almost absolutely constant voltage. These two sets of readings

are not presented here as an example of what may be done with the Bunsen photometer in the comparison of constant sources of light. They are indeed of no great accuracy, and contain larger accidental errors than some observations to which I shall have occasion to call attention presently. They exhibit, however, very clearly the existence of the personal errors of observation which are to form the subject of this paper.

TABLE I.

Two parallel sets of 10 readings upon the candle power of an incandescent lamp.

(1) (B. W. S. observing.)			(2) (E. L. N. observing.)		
Readings.	Differences.		Readings.	Differences.	
C. P.	C. P.	PER CENT.	C. P.	C. P.	PER CENT.
12.12	.112=	.91	12.56	.044=	.35
12.32	.088=	.72	12.60	.084=	.67
12.16	.072=	.59	12.36	.156=	1.25
12.16	.072=	.59	12.56	.044=	.35
12.28	.048=	.39	12.64	.124=	.99
12.40	.168=	1.38	12.60	.048=	.67
12.28	.048=	.39	12.56	.044=	.35
12.08	.152=	1.30	12.40	.116=	.93
12.12	.112=	.92	12.32	.196=	1.35
12.40	.168	1.24	12.56	.044=	.35
AVERAGES.					
12.232	.104	.852	12.516	.089	.717

It will be seen from the above table that while the apparent mean error of a single observation is only about one-tenth of a candle, and the probable error of each set only .022 candle, the two averages themselves differ by .284 candle.

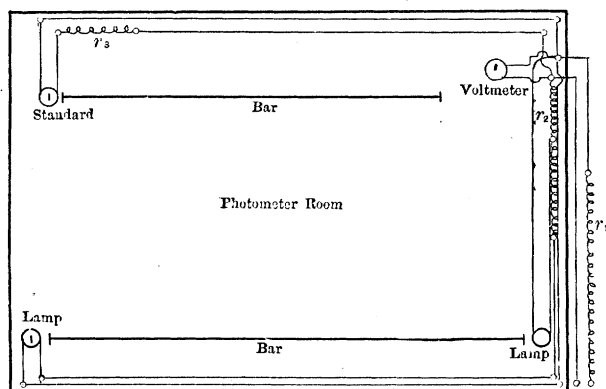
The following experiments were made for the purpose of determining the nature of this personal error:—

Three incandescent lamps of the same type and voltage were selected, care being taken to choose specimens, the carbons of which were as straight as possible. These lamps gave 16 candles at 110 volts. They were connected in multiple to the terminals of a storage battery giving a potential difference of 120 volts. Adjustable resistances of german silver wire were placed in the line leading to each lamp and in one of the mains leading from the battery. (See figure.)

The lamps, together with the above mentioned resistances, were set up in a photometer room which contained two Bunsen photometers. The connecting wires were of such length that the lamps could be moved from one photometer bar to the other without breaking connections. One of the lamps was set up as a comparison standard at the end of the shorter bar. Each of the other

lamps was then compared with this standard, the resistances being adjusted until the intensities of these lamps were found to bear the same relation to the standard. In other words, they were brought to the same intensity by a method which eliminated the systematic personal errors which it was my purpose to study.

The two lamps were then placed at the ends of the longer photometer bar, the length of which was 400 centimeters. It was divided into 800 equal parts. The lamps had been measured with the plane of the filament at right angles with the photometer bar, and care was taken in setting them up in their new position, to place them at the same angle and presenting the same face to the bar as before.



A closed circuit voltmeter between the terminals of the battery enabled the observer at the beginning of a set of readings to bring the lamps to the proper potential. In order to insure greater constancy in the degree of incandescence throughout the series of tests, the lamps were maintained at a potential considerably below the normal, their candle-power being about 12 instead of 16 candles.

A number of observers, all of whom were accustomed to photometric measurements, and some of whom had had extended experience, were asked to make a set of 10 readings each, upon the two lamps. The result of these two readings are given in table II.

TABLE II.

Ratio of two incandescent lamps, previously adjusted to equal brightness. The measurements are made in the usual manner, by means of the Bunsen photometer.

I_r and I_l are the intensities of the right-hand and left-hand lamps respectively.

Observer.	Ratio— $\frac{I_r}{I_l}$	Personal error.
A.....	1.0590 \pm .0040	— .0558
B.....	0.9704 \pm .0044	+ .0331
C.....	1.0021 \pm .0022	— .0189
D.....	1.0191 \pm .0072	— .0159
E.....	1.0182 \pm .0039	— .0150
F.....	1.0902 \pm .0057	— .0870
G.....	1.0733 \pm .0053	— .0701
H.....	1.0293 \pm .0042	— .0261
I.....	1.0297 \pm .0050	— .0263
J.....	1.0220 \pm .0027	— .0188

The true value of the ratio, $\frac{I_r}{I_l}$ determined previously by comparing each lamp separately with the standard, was $1.0032 \pm .0015$, which value was used in computing the personal error.

It will be seen from inspection of the table that none of the averages fall at the middle of the bar, nor are they distributed around it in such a manner that the most probable value of the entire series, calculated by least squares under the assumption that only fortuitous errors exist, approximates to unity as it should do, were the lamps of equal brightness and were there no systematic errors to vitiate the result. On the other hand the readings lie, with a single exception, on one side, namely to the left-hand of the centre of the photometer bar. It will be seen, moreover, that the probable error calculated for each set separately, without taking cognizance of any systematic error, is very small in comparison with the differences between the mean results of the various sets, and especially in comparison with the variations of those averages from unity.

The Bunsen disc with which these observations were made, was mounted in the usual manner, the two sides of the disc being viewed simultaneously by means of two plane mirrors set at the proper angle behind the former. It was noted that the almost universal habit in reading was to use the two eyes independently, one eye fixed on each side of the disc. It seemed probable, therefore, that the personal error arose from the unequal sensitive-

ness of the observer's eyes, in that he would unconsciously set the disc at too great a distance from the lamp which illuminated the side of the disc which was being observed by his more sensitive eye. It appears, if we accept this explanation, that the right eye was the more sensitive in all the cases under observation, excepting one, that of the writer (see table II. B), whose readings would indicate the opposite peculiarity.

In order to reverse the relation of the observer to the photometer bar, without altering any of the other conditions of measurement, a large mirror was set up opposite the photometer at a distance of about 40 centimeters. The observer by sitting with his back to the bar, could then see the images of the Bunsen disc in the mirror, and his right and left eyes were reversed with reference to the lamps. Sets of 10 readings were made in this manner by some of the same observers as before, the object being to test the hypothesis just stated. The results thus obtained were, however, complicated by the unforeseen circumstance that the method of using the eyes in observation was not the same when the image of the disc was seen in the mirror as when it was viewed directly. The observer, when using the mirror, no longer used his eyes independently, but scanned the image as a whole, so that both eyes had a share in determining the brightness of each side of the disc. The result was to produce a change in his settings, not by introducing a systematic error, equal and opposite to that occurring in the first series of observations, as had been expected, but by eliminating the error in question. In a word, the settings with the mirror were in better agreement than those made by direct observation, and they gave results much more nearly in accordance with the known equality of the lamps.

In my own case, however, an exception to the above statement must be noted, very possibly as the result of an effort to repeat with the mirror the precise method of observation followed in making the direct settings. I continued to use my eyes independently, viewing the image of one side of the disc, with the right eye, the other with the left. There resulted a set of readings, such as I had expected to obtain from all the observers, the mean of which lay as far from the centre of the photometer bar as the mean of the direct readings, but upon the other side. (Compare sets "B," table II. and III.)

The results obtained with the mirror are given in the following table :—

TABLE III.

Ratio of the two lamps determined by observing the images of the Bunsen disc in a large mirror; the observer placed with his back to the photometer bar:

Observer.	Ratio.. $\frac{I_r}{I_l}$	Personal error.
A.....	1.0070 \pm .0026	.0028
B.....	1.0444 \pm .0011	.0414
C.....	0.9964 \pm .0053	.0068
F.....	1.0141 \pm .0025	.0109
G.....	1.0004 \pm .0056	.0028
H.....	1.0134 \pm .0045	.0102
I.....	1.0004 \pm .0031	.0028

The observations with the mirror were followed by four sets of direct readings made with one eye bandaged. It was found that although more fatiguing, these monocular settings were made with a feeling of certainty on the part of the observer which had not accompanied the settings made with both eyes. In the latter case, indeed, a conflict between tendencies to set the disc in two distinct positions had been very apparent, the observer unconsciously choosing now one, now the other, as the true positions. The set of readings given in full in table IV., will serve to illustrate the result of this tendency. The instances in which the observer seems thus to have temporarily changed in his judgment of the true setting, are printed in heavy type.

TABLE IV.

No.	Reading.	No.	Reading.
1.....	1.033	6.....	1.048
2.....	1.022	7.....	1.053
3.....	1.021	8.....	1.023
4.....	1.023	9.....	1.033
5.....	1.050	10.....	1.030

This tendency to vacillation disappeared almost entirely when only one eye was used. The readings obtained with a single eye not only agreed much better among themselves than those made under like conditions, using both eyes, but the results obtained with the left eye were identical with those obtained with the right eye, and both seemed to be entirely free from the systematic personal error that had been found to vitiate readings made in the usual way.

The results of such a set of monocular readings, made by Mr. Snow and myself, all other conditions remaining the same as in previous trials, are given in table V.

It will be seen that the probable error of each set is much smaller than in the sets of observations made with both eyes; also that the readings of two observers whose mean results from similar sets with both eyes had differed by 8 per cent. (see sets "A" and "B," table II.), are in complete agreement.

Finally, it will be noted that the results of these four monocular series differ from the accepted value of the ratio of intensities of the two lamps (1.0032) by an amount less than the probable error of each set.

TABLE V.

Observer.	Eye used.	Ratio.	Personal error.
B. W. S.	(Right.)	$1.0028 \pm .0019$.0004
B. W. S.	(Left.)	$1.0001 \pm .0019$.0031
E. L. N.	(Right.)	$1.0001 \pm .0017$.0031
E. L. N.	(Left.)	$1.0031 \pm .0018$.0001

It had been my intention to extend the experiments described in this paper to a much larger number of observers. The evidence obtained, however, seemed quite sufficient to establish the existence of the personal error in photometry, and to show that it was in general very far from being a negligible quantity. Frequent repetitions showed, that in my own case at least, the error was very nearly constant; and I think that it would be quite possible to establish a personal equation, and to apply the proper correction.

A much better plan, however, would be to so modify the photometer car itself as to insure the use of both eyes in the inspection of each side of the illuminated disc. Several forms of photometer, already in use, partially fulfill the necessary requirement. Any device which would bring the images of the opposite faces of the disc into a vertical line in the field of view would doubtless serve to eliminate the error in question. Observations with such a photometer would correspond in character to the "monocular" readings given in table V. Not only would they be free from the systematic error to which the ordinary form of Bunsen photometer is subject, but the accidental errors would be much smaller, and the degree of uncertainty which attends the determination of candle-power by our present methods would be in great measure diminished.

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