

PAPERS

GLARE AND VISIBILITY*

A RESUMÉ OF THE RESULTS OBTAINED IN INVESTIGATIONS OF VISUAL
AND LIGHTING CONDITIONS INVOLVING THESE FACTORS

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SYNOPSIS: One of the most important and least explored phases of lighting is that complex and indefinite one which is known as *glare*. We commonly separate its causes into such components as excessive brightness of the light-source, excessive brightness-contrasts, and excessive quantity of light. Glare is generally considered, rather indefinitely, to result in impaired vision, decreased safety to the individual, visual and even bodily discomfort, injury to the visual organs, and even detriment to the health of the individual. Cause and effect are not always clearly differentiated. Definitions are not standardized and, of course, they cannot be until we have analyzed the causes and effects of glare.

That the problems before us in this field are complex and difficult of solution is evident if for no other reason than by the lack of analyses of glare into its components and the lack of data pertaining to these components. It seems advisable to simplify and clarify our discussion of glare by differentiating between glare and visibility by confining the term *glare* solely to us and the term *visibility* primarily to the object we wish to discriminate. In other words, an observer may experience discomfort due to a distribution of brightness which decreases the visibility of an object at which he is looking. We may also have decreased visibility due to a veiling-brightness without any discomfort to the observer. We may also have discomfort to the observer without any effect on visibility because the observer may not be in the act of discriminating anything. The terminology used here may not always be consistent because, for the sake of being understood, some of the older terms will be used notwithstanding their unsatisfactoriness.

The sections which follow are the briefest condensations of extensive investigations which have been prosecuted for the past two years in the Lighting Research Laboratory at Nela Park and which are still in progress. Sufficient space has not been provided for the inclusion of the numerous tables of actual data, therefore, only glimpses of some of the procedures and of the mean results are presented. Throughout these investigations two observers—a man and a woman—have faithfully subjected themselves to many trying ordeals. Their results were confirmed at strategic points in each test by a number of other observers. Therefore, it is felt that the

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results presented herewith are approximately the average of a number of observers whom we have no reason to believe are abnormal in their reactions to the causes involved. Many experiments with so-called colored lights have been carried on in these investigations, but they are not included here. In all cases in this paper the spectral character of the light is that obtained by modern high-wattage, gas-filled, tungsten-filament lamps.

SCOPE OF THE WORK

The foregoing synopsis is also intended as an introduction to this paper in which seven different phases of glare and visibility are presented. By no means is it implied that these aspects are distinctly independent of each other. On the contrary they are complexly interwoven. For example, we use the terms *veiling-glare*, *dazzle-glare*, and *blinding-glare*. These three kinds of glare have something in common and to this extent may be considered to be three *degrees* of glare. As a matter of fact, our work suggests that the decrease in visibility due to a veiling-brightness or a dazzling light-source near the line of vision is due finally to the same phenomenon in the visual process. It should be noted that these two terms have arisen largely from considerations of the objective rather than the subjective phenomena.

Veiling-Glare.

This might be better termed *veiling-brightness* because glare in a restricted sense often is not involved even though visibility is greatly reduced. This is produced by light more or less uniformly superimposed on the retinal image, thus reducing contrasts and hence visibility. It is illustrated by illuminated fog or smoke; by light more or less diffusely transmitted by the "window" of a so-called "transparent envelope;" by images of bright objects reflected from the glass of a show-window, from glossy paper, from glossy signs, from glass covers of pictures. It may also result from light *scattered* in the eye from powerful light-sources in the field of vision. Possibly it is due to a "diffusion" of retinal processes or even of sensations.

Dazzle-Glare.

This is the most common type of glare. It reduces visibility and may be barely noticeable, distracting, discomforting or painful. It may be said to be produced by any light entering the eye

which does not aid vision. Even *veiling-glare* may be dazzling. An example is a light-source in the visual field which is annoying to the observer. The retinal image of this light-source theoretically may be quite separated from the retinal image of an object which an observer is looking at, but there is some kind of confusion produced perhaps by scattering of light in the eye, or by spreading of the retinal processes or a diffusion of sensations. Even when an individual is not concerned with visibility, the retinal images of sufficiently powerful light-sources in certain parts of the visual field may be annoying, distracting, discomforting or painful; that is, *dazzling*. Perhaps no better term can be proposed, but at least the term *dazzle-glare* will not become perfectly clear without being well defined and consistently used.

Blinding-Glare.

This may be considered the highest degree of glare. It is due to retinal images of extreme brightness which reduce for a time the ability of the retina to respond normally to light. The term may be confined to a condition which fatigues the retina to such an extent by over-exposure to excessive brightness to cause *blinding* after-images to persist for some time. It has been termed *scotomatic glare*. Of course, any kind of glare may be more or less *blinding*, but likewise any kind of glare may be more or less *veiling* or *dazzling*. Definition and usage can establish any reasonably satisfactory term and simplicity goes a long way toward making a term satisfactory.

Irradiation.

Irradiation is the term applied to the apparent increase in the size of an object which is brighter than its surroundings. It may be due to a spreading of the retinal image beyond its actual confines as determined by geometrical optics or it may be due to diffusion of retinal processes or sensations. We need not concern ourselves here with an explanation of the phenomenon.

Growth and Decay of After-Images.

Time is required for the visual process to reach its final normal state when a retinal stimulus is created or discontinued. We are concerned here chiefly with the decay of the *after-images* of bright light-sources. Gradual or normal change in the sensibility

of the visual process with changes in the brightness of the visual field is termed *adaptation*. If the visual process is adapted to a certain brightness, it takes time for the effect of this brightness to disappear after the stimulus has actually been cut off. This after-effect is the *after-image*. The persistence of an after-image increases with the brightness and duration of the stimulus (and varies somewhat with the spectral character of the light).

Psycho-Physiological Effects of Light-Sources.

It was found that this phase could be studied best by exposing the light-source to view only for a short period. When the light-source is exposed to view the observer appraises its pleasantness, discomfort, etc., by his physical and mental experience in general. Doubtless this experience is partially due to the visual process attempting to adapt or adjust itself to the stimulus. No very serious attempt as yet has been made to find out why the effects are produced. An arbitrary scale of thirteen steps was devised, as seen later, the limits being termed *scarcely noticeable* and *irritating* or *painful* respectively. The eighth step in the scale is that condition which is at the boundary of comfortable and uncomfortable. In other words, the first seven steps are on the side of *comfortable*; the last five steps are on the side of *uncomfortable*.

The Size of the Pupil of the Eye.

This is important because the pupil is the visual doorway. It determines the amount of light entering the eye and, therefore, the brightness of the retinal image. It determines to some extent the effectiveness of proper lighting as well as the harmfulness of improper lighting. Its size fluctuates with the lighting conditions and with the distance of the object viewed. It varies appreciably in diameter with the brightness and position of light-sources and other bright areas. When we have completely analyzed glare and visibility, possibly the size of the pupil may be used as a means of appraising lighting conditions.

SYMBOLS AND TERMS

The following symbols are employed throughout this paper:

A = apparent increase of the visual angle in minutes of a bright strip viewed against a darker background; or conversely it is the apparent de-

crease of visual angle in minutes of a dark strip seen against a brighter background.

d = visual angle in minutes subtended by a given object.

B = brightness in millilamberts of a light-source in the field of view of an observer.

B_1 = brightness in millilamberts of a "veiling-glare."

B_2 = brightness in millilamberts of the background of the test-object in the test of irradiation.

F = brightness in millilamberts of the field surrounding the test-object, or of the field to which the eyes are adapted.

E = the meter-candles of illumination at the eyes of an observer from a light-source in the field of view.

f = reflection-factor of the test-object.

f_1 = reflection-factor of the background of the test-object or of the surrounding field.

R = distance in centimeters between the eyes of the observer and the test-object and is the distance for which the eyes are accommodated.

Q = solid angle in steradians subtended at the eyes of an observer by a light-source of a square centimeters of projected area placed at a distance of r centimeters from the eyes; or $Q = \frac{a}{r^2}$. When a/r^2 equals unity we have one steradian—the unit solid angle.

D = angle in degrees between the center of a light-source and the line of vision.

P = the observed diameter in millimeters of the pupil of the eye.

S = the time in seconds the eyes are exposed to a light-source in the center of the visual field.

T = time in seconds elapsed since the end of an exposure of the eyes to a light-source.

K = logarithmic constant expressing the magnitude of the "psycho-physiological sensation."

V = *visibility-factor* or the ratio of the brightness of the background of the test-object to the difference in brightness between the background and the test-object. For any given ordinary condition, visibility-factor varies from $V = 1$ for maximum clearness to about $V = 100$ for the other limit (barely perceptible).

All logarithms are expressed in the Common System in which 10 is the base.

One millilambert (ml) is the average brightness of a perfectly reflecting and diffusing surface having an illumination of 10 meter-candles or 0.93 foot-candles; or it is the brightness of a perfectly diffusing surface having an 80 per cent reflection-factor and an illumination of 1.16 foot-candles.

The brightness of a diffusely reflecting surface in millilamberts is equal to the diffuse reflection-factor times the number of foot-candles

divided by 0.93; or it is equal to the diffuse reflection-factor times the number of meter-candles divided by 10.

1,000 millilamberts or one lambert is the brightness of a perfectly reflecting and diffusing surface emitting 2.054 candles per square inch. One candle per square inch equals 487 millilamberts.

IRRADIATION

Various types of test-objects were used in determining the magnitude of the effects of irradiation. The results were substantially the same for all of them. One of these test-objects was an opaque ring of 34 mm. (1.34 in.) outside diameter and of such inside diameter as to give a radial width of the ring subtending a visual angle of A minutes at a distance of 344 cm. (135 in.). This is shown in Fig. 1. The ring was placed in

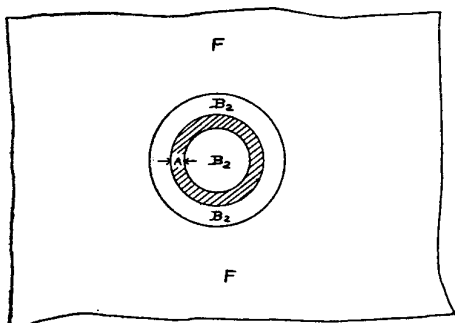


FIG. 1.—The test-object used in the investigation of irradiation. The surrounding field had a brightness of F millilamberts. The opaque ring of radial width of A minutes was viewed against a background of brightness B_2 millilamberts.

front of a diffusing glass which was uniformly illuminated to a brightness B_2 as seen by the observer. Thus the opaque ring was seen against a circular background of brightness B_2 . The surrounding field (relatively much greater than shown in Fig. 1) was a white cardboard illuminated to a brightness F . A movable shield of white cardboard could be interposed behind the circular opening in the surrounding field and in front of the opaque ring so as to obscure it when desired. In making the observations the eyes were first adapted to the field brightness F with the shield in the circular opening also at a brightness F .

Then the shield was suddenly withdrawn so that the opaque ring was revealed against its bright background of brightness B_2 . The brightness B_2 was adjusted until it was of such a value that at the moment of exposure the irradiation was just sufficient to render the opaque ring invisible.

The experiment was repeated for various brightnesses of the surrounding field F and for various widths (A minutes) of the ring. The brightness B_2 of the background was determined in

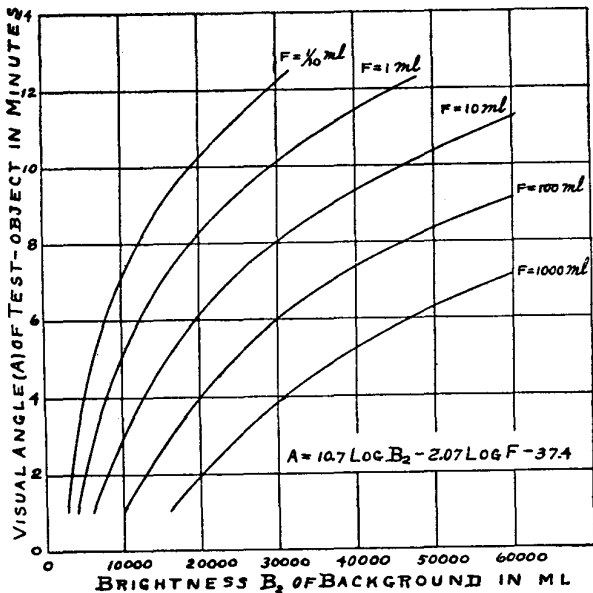


FIG. 2—Showing the results of irradiation by determining the visual angle of an object rendered just invisible by irradiation due to its bright background B_2 for five different degrees of adaptation or brightness F of the surrounding field.

each case at which the ring was just rendered invisible by irradiation. The results may be expressed by the empirical equation.

$$A = 10.7 \log B_2 - 2.07 \log F - 37.4.$$

The relations of visual angle A to the brightness of the background B_2 which rendered the ring just invisible by irradiation

are plotted in Fig. 2 for several brightnesses of the surrounding field F . These values of F are 0.1, 1, 10, 100 and 1,000 millilamberts respectively.

VEILING-GLARE

The test-object T in Fig. 3 was a ring of gray paper viewed against a background of brightness F . The test-object and the

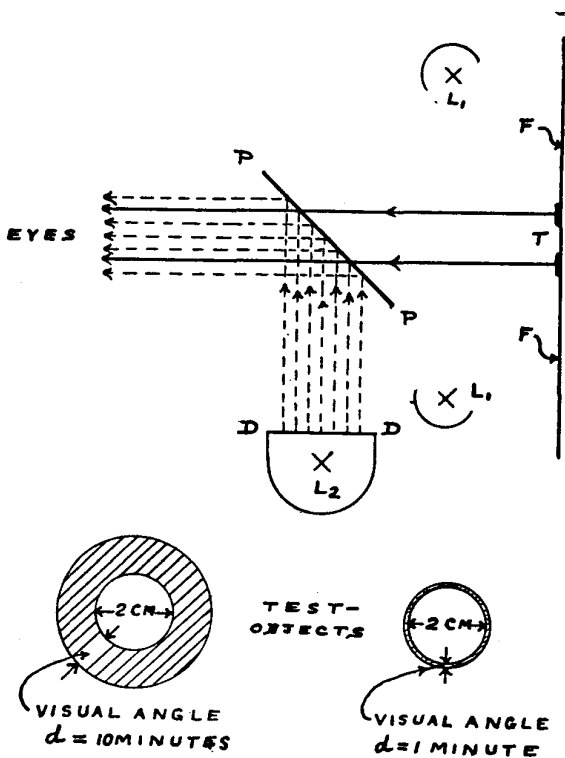


FIG. 3—A diagram of the apparatus used in studying "veiling-glare."

surrounding field F were illuminated by the light-sources L_1 . A plate glass P was interposed at an angle of 45 degrees. This pro-

duced a veiling-brightness by reflecting an image of a diffusing glass D which was illuminated by the light-source L_2 . Several test-objects were used and all gave results in general accord. The ring of gray paper has an inside diameter of 2 cm. (0.8 in.) and an outside diameter such as to have a radial width which subtended a visual angle of d minutes at a distance of 344 cm. (135 in.) from the observer's eyes. Two of the rings are indicated in Fig. 3. The reflection-factor of the test-object was f and that of its background was f_1 . The veiling-brightness (reflected image of D , Fig. 3) was B_1 .

Since the background of the test-object has a brightness of F when its reflection-factor is f_1 , the difference in brightness between the test-object with a reflection-factor of f and its background is $F - f \frac{F}{f_1} = F \frac{f_1 - f}{f_1}$. The transmission-factor of the plate glass being about 90 per cent, the difference between the brightness of the test-object and its background as seen by the eye is only $0.9 F \frac{f_1 - f}{f_1}$. The apparent brightness of the background as seen by the eye is the sum of that transmitted by the glass, (which is $0.9 F$), and the brightness of the reflected light (which is B_1). Thus the apparent brightness of the background of the test-object is $0.9 F + B_1$. The visibility-factor V is the ratio of the apparent total brightness divided by the apparent difference in brightness between background and the test-object. Therefore,

$$\text{visibility-factor, } V = \frac{.9 F + B_1}{.9 F \frac{f_1 - f}{f_1}}$$

The visibility-factor V for any observer depends upon the visual angle of the test-object, the effort exercised by the observer in seeing, and the total apparent brightness of the background of the test-object, that is, the adaptation of the eyes.

When the ability of an observer is taxed to the limit, that is, when the observer can just detect the presence of the test-object, it was found that the visibility-factor increased with the visual angle d of the test-object according to the following empirical equation:

visibility-factor, $V = M (d - .5)^4$.

Here M is practically a constant, having a value between 40 and 50 for the test-object used for apparent total brightnesses of background from 1 ml. to 400 ml. and for values of visual angle d from 0.75 minute to 12 minutes. The visibility-factor appears to attain a maximum for values of d between 12 and 15 minutes. Fig. 4 shows this relation of visual angle d and visibility-factor V and gives average limiting values of visibility-factor for a number of observers for apparent total brightnesses of background from 1 ml. to 400 ml. and for values of visual angle d varying from 0.75 minute to 12 minutes. Therefore for these limits the vis-

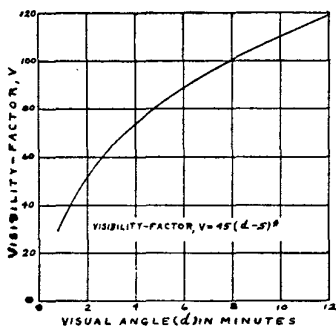


FIG. 4—Showing the relation between visual angle (d minutes) of the test-object and the visibility-factor V for the limit of visibility. This relation was found to hold between the limits of total apparent brightnesses of background from 1 ml. to 400 ml.

ibility-factor for the average observer is given by the empirical equation,

$$\text{visibility-factor, } V = \frac{.9 F + B_1}{.9 F \frac{f_1 - f}{f_1}} = 45 (d - .5)^4.$$

If instead of measuring the actual brightness F of the background of the test-object we measure its brightness as transmitted through the plate glass and express it by F_1 , the apparent difference in brightness between the test-object and its background is $F_1 \frac{f_1 - f}{f_1}$. Similarly, the veiling-brightness is B_1 and

the background of the test-object is $F_1 + B_1$. Therefore,

$$\text{visibility-factor, } V = \frac{F_1 + B_1}{F_1 \frac{f_1 - f}{f_1}} = 45 (d - .5)^4$$

for values of visual angle d between 0.75 minute and 12 minutes and values of total apparent brightness between 1 ml. and 400

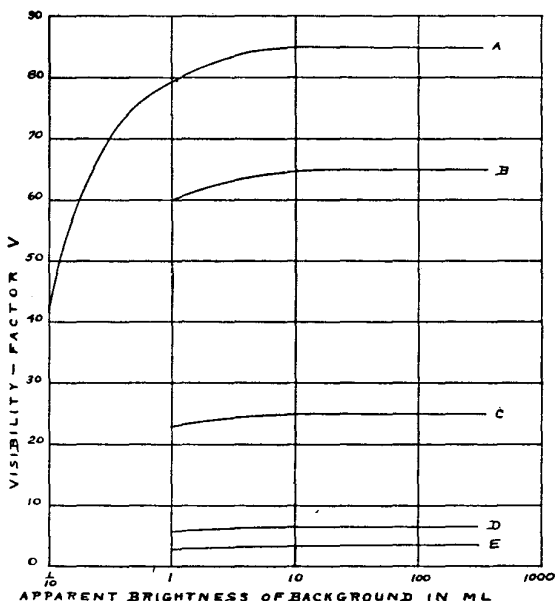


FIG. 5—Showing the dependence of visibility-factor upon adaptation or upon the apparent brightness of the background of a test-object having a visual angle of 5 minutes. *A* is for the limit of vision; *B*, for the practical limit of vision; *C* for greatly impaired vision; *D* for appreciably impaired vision; and *E* for practically unimpaired vision.

ml. For values of total apparent brightness of background of test-object below 1 ml. the visibility-factor is less than that given by the above equation. This is shown by Curve *A* in Fig. 5.

The value of the visibility-factor for various degrees of comfort or ease in seeing appears to be a logarithmic function, which

increases very rapidly with increasing effort or discomfort in seeing. In a test with visual angle d of test-object equal to 5 minutes (Fig. 5),

visibility-factor = 1.0 for maximum clearness of vision.

visibility-factor = 3.5 for practically unimpaired vision (curve E).

visibility-factor = 6.1 for appreciably impaired vision (curve D).

visibility-factor = 24.0 for very greatly impaired vision (curve C)

visibility-factor = 66.0 for practically the limit of visibility (curve B).

visibility-factor = 85.0 for the very limit of visibility (curve A).

As an illustration of the effect of veiling-brightness let us consider an object in a show-window subtending an angle of 5 minutes for the observer and having a brightness one-half that of its background or vice versa. If the brightness of the sky or a sunlit object is 10,000 millilamberts and this image is reflected from the plate glass, the object viewed in the show-window will be obscured if its background is less than 20 millilamberts. If the object is to be seen even with great difficulty its illumination intensity must be increased three or four fold.

DAZZLE-GLARE

A great number of tests have been made to determine the "blinding effects" of light-sources within the field of view located at an angle to one side or above the line of vision. In the arrangements for this test shown in Fig. 6, the test-object was placed upon a screen illuminated to a brightness F . A light-source was placed with its center at an angle of D degrees above the line of vision of the observer. This light-source consisted of a diffusing spherical ball in a light-tight box over the front of which could be placed cardboard shields containing circular openings of various sizes. The brightness of the light-source was B and its size was such that its area subtended a solid angle of Q steradians at the eyes of the observer and that it produced an illumination of E meter-candles at the eyes of the observer. It may be noted here that $E = \frac{10}{\pi} BQ$. The test-objects used most were of the same type as the one described in the investigation of veiling-brightness.

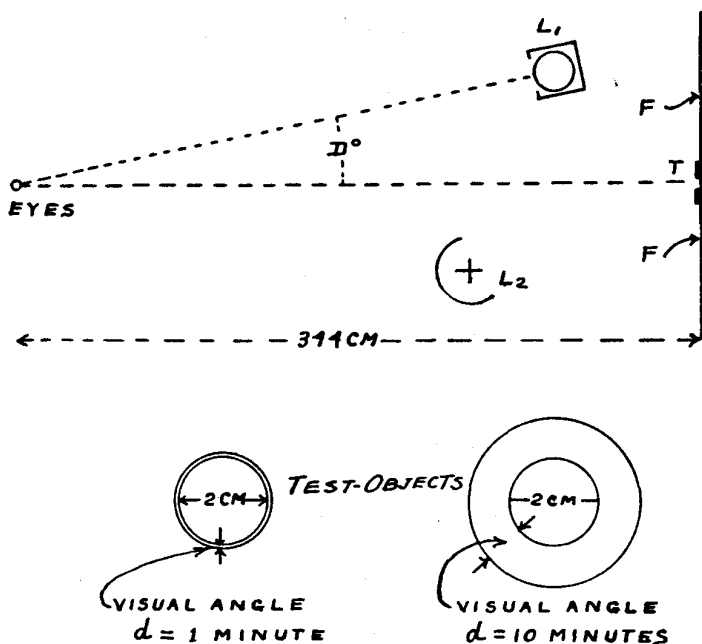


FIG. 6—Showing the set-up used in investigating "dazzle" glare. The "dazzle" light-source L_1 was at an angle of D degrees with the line of vision. The test-object T consisted of a ring on a background 344 cm. (135 in.) from the observer. The light-source L_2 illuminated the background to a brightness F .

In making this investigation the procedure was very similar to that employed in the veiling-brightness test, and the results are strikingly similar; that is to say, in "dazzle-glare" the visibility factor,

$$V = \frac{F + 4 \frac{E}{D^2}}{F \frac{f_1 - f}{f_1}} = 45 (d - .5)^4$$

whereas in "veiling glare" the term $\frac{4E}{D^2}$ is replaced by B_1 , the veiling-brightness. It was found by actual experiment that the

decrease in visibility due to "dazzle-glare" was also producible by a certain "equivalent" veiling-brightness. Thus it appears that due to diffusion, reflections, or other causes at work in the media of the eye or diffusion somewhere in the visual process, the resultant effect is the same as a superposed brightness approximately proportional to the intensity of illumination E of the "dazzle" light at the eye of the observer and approximately inversely as the square of the angle which these light rays make with the line of vision. This equation was found to hold for brightnesses F of the field between about $\frac{1}{10}$ ml. and 100 ml. and for values of visual angle d from 0.75 to 12 minutes. For lower values of F the visibility-factor decreases as shown previously in A , Fig. 5.

By introducing veiling-brightnesses of different magnitudes, the values of these were determined for decreases in visibility equivalent to those produced by the dazzle-source at various angles D above the line of vision. The dazzle-source was maintained constant in size, in brightness, and therefore, in intensity. It produced a constant illumination E at the eyes for each series of observations. In Fig. 7 the results are shown for the series when E was 100 meter-candles at the eyes. It will be observed that dazzle-glare becomes relatively insignificant at 30 degrees.

If there are two or more light-sources at angles D_1, D_2, D_3 , etc., to the line of vision giving respectively E_1, E_2, E_3 , etc., meter-candles of illumination at the eyes of the observer, then the equivalent brightness $4 \frac{E}{D^2}$ for dazzle-glare is replacable by

$$4 \frac{E_1}{D_1^2} + 4 \frac{E_2}{D_2^2} + 4 \frac{E_3}{D_3^2} \dots = 4 \sum \frac{E}{D^2}.$$

Since a relatively concentrated light-source having a uniform brightness of B and an area subtending a solid angle of Q steradians with the eye, the illumination E in meter-candles at the eye of the observer is $E = \frac{10}{\pi} BQ$. Now if instead of there being one or more light-sources, each of which is practically concentrated at a point, the glare surface is a relatively large area,

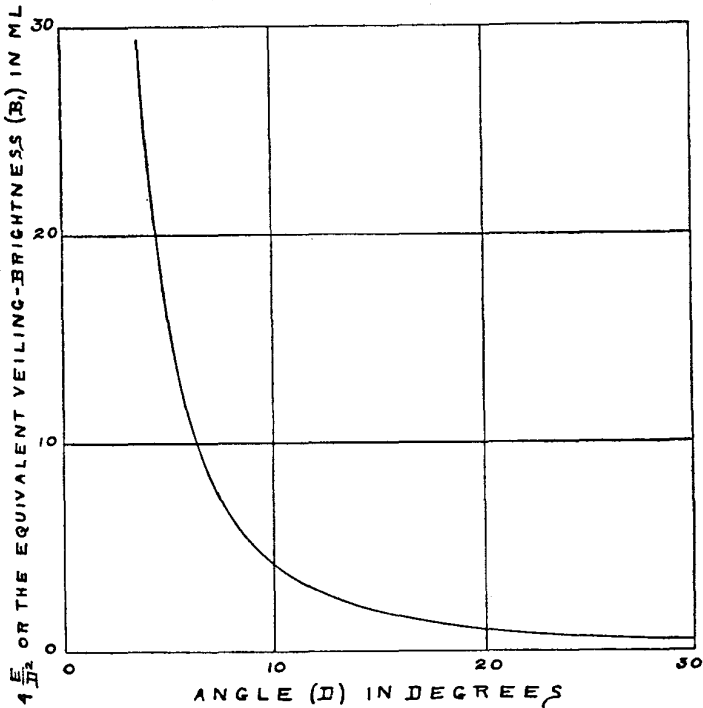


FIG. 7—Showing the values of veiling-brightness producing the same decrease in visibility as a dazzle-glare source at various angles D above the line of vision. In all cases the dazzle-glare source produced an illumination E of 100 meter-candles at the eyes.

then the equivalent brightness of the dazzle glare imaged upon the central retinal area is

$$4 \sum \frac{E}{D^2} = 4 \frac{10}{\pi} \sum \frac{B \Delta Q}{D^2}$$

when ΔQ is the elementary solid-angle subtended by an element of area of brightness B at an angle D to the line of vision.

Therefore, the final equations for the limiting visibility-factor for dazzle glare is

$$\frac{F + 4 \sum \frac{E}{D^2}}{\frac{F(f_1 - f)}{f_1}} = \frac{F + \frac{40}{\pi} \sum \frac{B \Delta Q}{D^2}}{\frac{F(f_1 - f)}{f_1}} = 45 (d - .5)^{.4}$$

for values of visual angle d between 0.75 minute and 12 minutes and field brightness F from about $\frac{1}{10}$ ml. to 100 ml.

These tests were made under most diverse conditions with a number of observers. Space is not available for presenting many details and the tables of results obtained, but the equations represent the average data for normal eyes under extremes of conditions for normal usage. They also represent very well the data obtained with colored lights. The effect of the location of a "dazzle-glare" source D degrees above the line of vision is shown in Fig. 8 for equally "dazzling" conditions. For example, a 25-

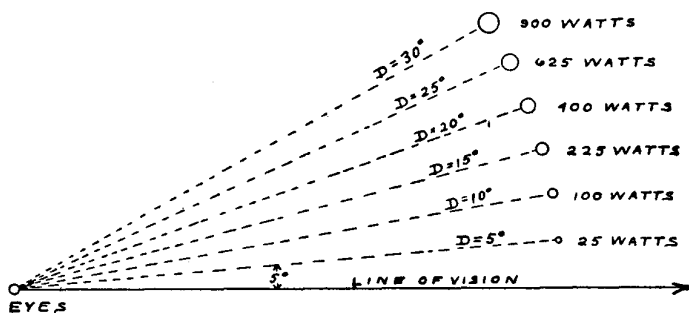


FIG. 8—Location of various sizes of tungsten lamps above the line of vision for equal dazzle-glare.

watt tungsten lamp 5 degrees above the line of vision is as "dazzling" as

- a 100-watt lamp 10 degrees above the line of vision.
- a 225-watt lamp 15 degrees above the line of vision.
- a 400-watt lamp 20 degrees above the line of vision.
- a 625-watt lamp 25 degrees above the line of vision.
- a 900-watt lamp 30 degrees above the line of vision.

Dazzle-glare practically ceases when the light-source is more than 30 degrees above the line of vision. The eye-brows in some cases are quite effective in shielding the eyes of many persons from light-sources above this angle. In fact in some cases it was found that the eye-brows become effective shields for light-sources above 25 degrees above the horizontal.

BLINDING-GLARE

The purpose of this test was to determine the size and brightness of a light-source which would just produce a distinct sense

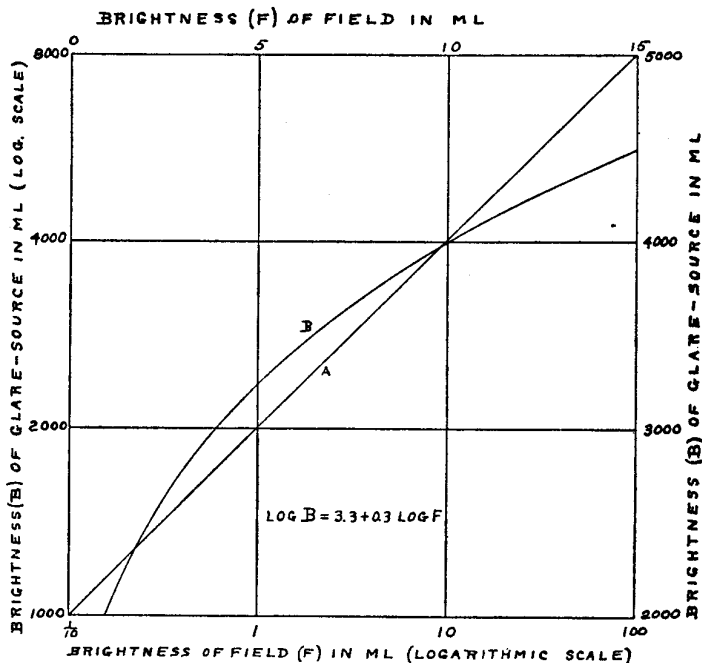


FIG. 9—Showing the relation of brightness F of the adapting field and the brightness B of a glare-source when it is just of "blinding" brightness. Curve A is plotted to logarithmic scales and Curve B to arithmetical scales (upper and right-hand scales).

of over-exposure or produce an unquestionable sensation of glare. The arrangements for the test consisted of a white screen with

a circular opening, behind which was placed a large tungsten lamp in a white diffusing spherical globe and in front of which was placed a movable shield under the control of the observer. The size of the projected area of the lamp globe seen by the observer was varied by placing over the opening in the surrounding field various diaphragms with circular openings concentric with the opening in the screen. The brightness of the front of the screen was F and the observer was seated at a distance of 244 cm. (96 in.) in front of the screen.

In making an observation, the size of the glare-source was first fixed and the illumination of the surrounding field was adjusted to give a uniform brightness F . Then the brightness of the glare-source was varied until the observer was satisfied that it was just of a "blinding" brightness. It was found that variations in the diameter of the glare-surface from 1.8 cm. (0.7 in.) to 30.5 cm. (12 in.) had little or no influence upon the results. The relation of brightness B of the glare-surface and the brightness F of the surrounding field, from $1/10$ ml. to 100 ml. is represented by empirical equation,

$$\log B = 3.3 + 0.3 \log F.$$

The average results for several observers are shown in Fig. 9.

GROWTH AND DECAY OF AFTER-IMAGES

In order to determine the rate of decay of after-images resulting from exposures under varying conditions, several investigations were carried out. The arrangement for the tests consisted of an adapting field or screen placed 344 cm. (135 in.) from the eyes of the observer illuminated to a brightness F . The glare-surface, consisting of a tungsten lamp in a white diffusing globe having a brightness B , was placed behind an opening in the screen. A movable shield covered the opening. One portion of the shield was covered with black velvet and another portion with white paper. The shield was arranged so that either portion of the shield could be used to cover the opening at any time.

The first test was with a 5 cm. opening in the screen. The mode of procedure consisted in permitting a previously formed

image to completely die away then adapting the eyes for about one minute to the brightness F of the adapting field. The light-source was then exposed 4 seconds after which it was covered with the velvet-coated portion of the shield, the observer keeping his eyes fixed upon the shield. The time T_1 in seconds for the after-image to decay to an apparent brightness of the surrounding field of brightness F was measured. The test was made with a range of brightnesses of the surrounding field from 0.06 ml. to 100 ml. and with brightnesses B of the light-source from 675 ml. to 53,000 ml. The results of this test are represented by the empirical equation,

$$\text{Log } T_1 = 1.26 \log B - 0.31 \log F - 4.54.$$

The average results for several observers are plotted in Fig. 10.

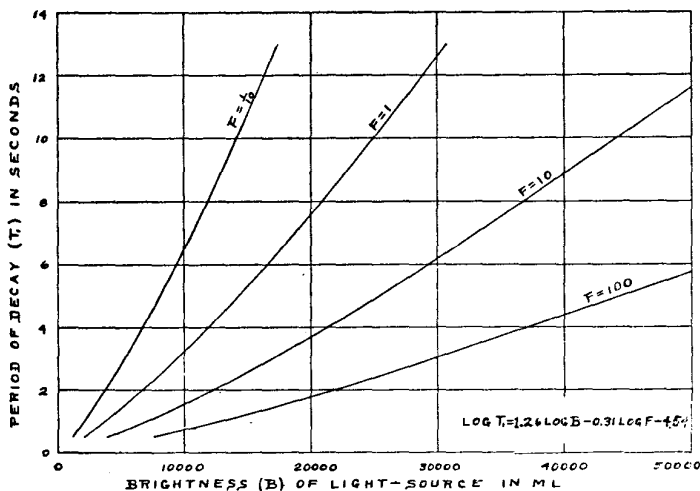


FIG. 10—Showing the period of time T_1 in seconds for an after-image to decay to an apparent brightness F of the adapting field, after the eyes had been previously adapted to a brightness of F ml. and then exposed for four seconds to a light-source of brightness B .

The second test consisted of finding the brightness B of the light-source for a 4-second exposure which produced an after-image of the same apparent brightness as the surrounding field at the instant the light-source was covered. In this test the

brightness F of the surrounding field was varied from 0.075 ml. to 1,950 ml. and the brightness B of the glare-surface was varied from 600 ml. to 53,000 ml. The results of the test are represented by the empirical equation,

$$F = \left[\frac{B}{1480} \right]^4$$

The third test was made with the opening of 5 cm. diameter in the screen as in the two preceding tests and the portion of the shield covered with white paper of the same reflection-factor as the surrounding field used to cover the opening after the exposure. After properly adapting the eyes as before to a brightness F , the test consisted in exposing the eyes to the light-source of brightness B for 4 seconds and then measuring the time T_2 in seconds for the after-image to decay sufficiently to be unnoticeable when viewing any portion of the adapting field. The results of this test are represented by the empirical equation,

$$\text{Log } T_2 = 1.1 \log B - 0.31 \log F - 3.08.$$

This test was made for a range of brightness F of the adapting field from 0.06 ml. to 100 ml.; with brightness B of the light-source from 675 ml. to 53,000 ml.; and for a time of exposure S of four seconds.

The fourth test was made with a light-source of 14.5 cm. (5.7 in.) diameter and a test-object placed on the front of the shield or on the screen. The test-object consisted of a gray circular ring having an inside diameter of 2 cm. and an outside diameter such as to give a radial width of d mm. or a visual angle of d minutes at the distance of the screen of 344 cm. (135 in.). The reflection-factor f_1 of the background of the test-object was 0.75, but the reflection-factor f of the gray ring test-object was varied from 0.72 to 0.04.

In making the test the brightness of the adapting field F was varied from $\frac{1}{10}$ ml. to 50 ml.; the brightness B of the light-source from 450 ml. to 11,500 ml.; the visual angle d of the test-object from 1 to 6.2 minutes; the time of exposure S from 1 to 8 seconds. The time T was measured in seconds for the after-image to decay sufficiently for the test-object to be discernible.

An empirical equation representing approximately the average results for the visual angle d of the test-object equal 1 minute was found to be,

$$\text{Log } T = 1.16 \log B - .32 \log F + .9 \log S - .4 \log \frac{f_1 - f}{f_1} - 4.84.$$

Having noticed a similarity of the effects of after-images and veiling-glare on visibility, an effort was made to determine the relation between them. It was noted that an after-image has a similar effect in obscuring a test-object as veiling-glare; and that a veiling-brightness B_1 has an effect in reducing visibility equivalent to an after-image produced by an exposure for S seconds to a brightness of B , which has decayed for T seconds after the end of the exposure, that is,

$$B_1 = \left[\frac{BS}{yT} \right]^x$$

where x is a constant having a value of 3 to 4 and y is a constant. If x is 3, the corresponding value of y is 4,000 and if x is 4 the corresponding value of y is 5,000. Therefore,

$$B_1 = \left[\frac{BS}{4000T} \right]^3 \quad \text{or} \quad B_1 = \left[\frac{BS}{5000T} \right]^4$$

An equation for the visibility-factor for the limit of vision is

$$\text{visibility-factor, } V = \frac{F + \left[\frac{BS}{4000T} \right]^3}{F \frac{f_1 - f}{f_1}} = 45 (d-.5)^{.4} \quad \text{or}$$

$$\text{visibility-factor, } V = \frac{F + \left[\frac{BS}{5000T} \right]^4}{F \frac{f_1 - f}{f_1}} = 45 (d-.5)^{.4}$$

These equations represent the results fairly well between the limits of F from 1 ml. to 50 ml., of B from 500 ml. to 12,000 ml.,

of S from 1 second to 8 seconds, and of visual angle d from 1 minute to 6 minutes. For brightness F of the adapting field below 1 ml., the visibility-factor is somewhat less than in the above equations as shown in A , Fig. 5.

Fig. 11 shows the number of seconds T which must elapse

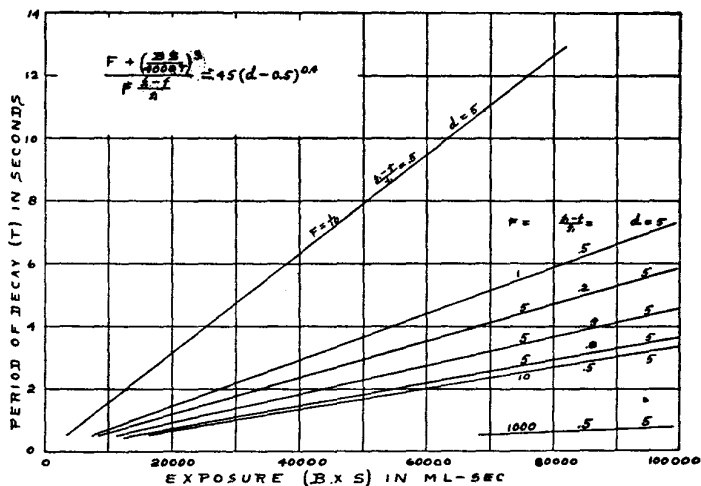


FIG. 11.—Showing the number of seconds T which must elapse after an exposure of the eyes for S seconds to a light-source of brightness B before a test-object upon the background may be seen. The test-object of reflection-factor f and of visual angle d minutes was viewed against a background of reflection-factor f_1 and of brightness F . Before the exposure the eyes were adapted to the brightness F . Curves are shown for seven conditions.

(after an exposure of S seconds to a light-source of brightness B) before a test-object of reflection-factor f (having a visual angle of d minutes) can be seen against the adapting field of brightness F and of reflection-factor f_1 .

PSYCHO-PHYSIOLOGICAL EFFECTS OF LIGHT-SOURCES

An attempt was made to determine by two methods of test the conditions of equal "shock" or "effect" when light-sources are exposed momentarily. One method is comparative and the other

is absolute. It was found easier for the observer to appraise the effect when the exposure was brief than when it was prolonged.

In using the comparative method of test, an adapting field of a brightness F was placed 344 cm. (135 in.) in front of the observer. At one side of the center of the screen a comparison light-source of constant size and brightness was screened from view excepting when a comparison was being made. At the other side of the center of the screen a similar light-source of variable size and brightness was located and normally screened by a movable shield which could be quickly withdrawn at will. By maintaining the comparison light-source fixed and varying the size and brightness of the other, curves of equal "shocks" or "sensations" for momentary glimpses of light-sources of various sizes and brightnesses were obtained.

When the absolute method of test was employed, only the light-source of variable size and brightness was employed. In making an observation the area of the light-source was first adjusted and then its brightness was adjusted to some criterion—for example, "maximum pleasure." Then its area was varied and its brightness again adjusted to give the same sensation for a momentary glimpse. In this way curves of equal "shock" or "sensation" were obtained for diverse conditions.

Results arrived at by the two methods of test showed good agreement, especially when only the area of the light-source and its brightness were varied. Denoting the area of the light-source by the solid angle Q steradians subtended by the area, expressing the brightness of the screen or adapting field by F , and denoting the brightness of the light-source by B , an empirical equation was obtained for the "sensation" as follows:

$$K = \log B + .25 \log Q - .30 \log F.$$

Here K is a measure of the sensation or shock when the light is momentarily exposed to view. By averaging the results of a number of observers when varying F from $1/10$ ml. to 100 ml., varying B from 1 ml. to 30,000 ml., and varying the size of the light-source from 0.88 cm. (0.35 in.) to 30.5 cm. (12 in.) at 344 cm. (135 in.) distance, the following values for K were obtained:

- 0.32 when sensation is scarcely noticeable.
 0.62 when sensation is most pleasant.
 0.97 when sensation is still pleasant.
 1.26 when sensation is at limit of pleasure.
 1.46 when sensation is very comfortable.
 1.70 when sensation is still comfortable.
 1.80 when sensation is less comfortable.
 1.90 when sensation is at boundary between comfort and discomfort.
 2.21 when sensation is perceptibly uncomfortable.
 2.36 when sensation is uncomfortable.
 2.52 when sensation is thoroughly uncomfortable.
 2.59 when sensation is at boundary between objectionable and intolerable.
 2.77 (and above) when sensation is irritating (higher values painful).

The empirical equation shows that a light-source which is unpleasant to view against a field of low brightness F may be rendered pleasant by either increasing the brightness of the surrounding field F or by viewing it from a greater distance (smaller value of subtended angle Q).

THE SIZE OF THE PUPIL OF THE EYE

It has been shown in connection with dazzle-glare that a light-source which gives a directional component of E meter-candles at the eye when at an angle of D degrees above the line of vision, produces a glare effect of the same magnitude as a veiling-glare of brightness B_1 where

$$4 \frac{E}{D^2} = B_1.$$

It would appear then that the equivalent brightness B_1 is proportional to the quantity of light that enters the eye from the dazzle-source.

In order to study the influence of the pupillary opening upon the magnitude of dazzle-glare a pupilometer was constructed consisting of a telescope in which a 45-degree prism reflected the image of an illuminated scale into one-half its field, and the image of the pupil to be measured filled the other half of its field. Several dazzle-glare investigations were made in a manner similar to the ones previously described in which the diameter of the pupil of the observer's eye was measured. The results of these indicate that the brightness of the equivalent veiling-glare is proportional to the projected area of the pupil at right angles

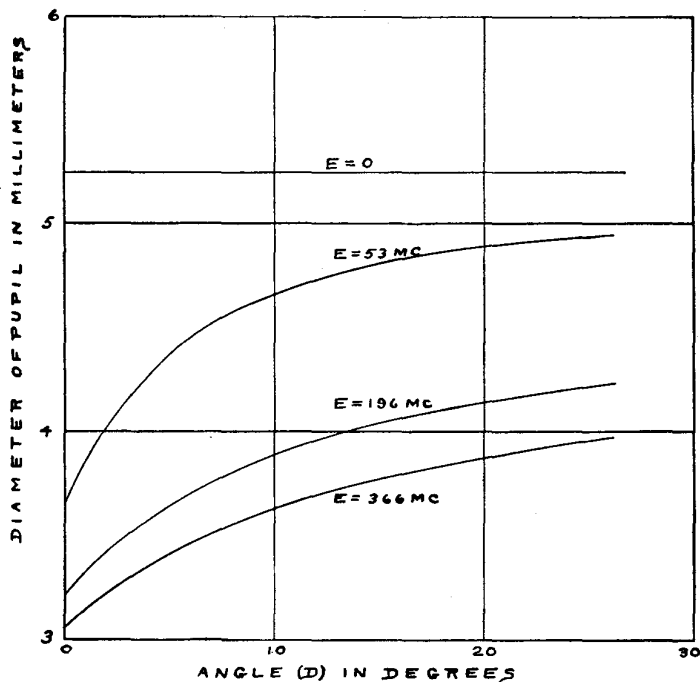


FIG. 12—Showing the variation of pupil diameter P with the angle D which a dazzle light-source makes with the line of vision when the brightness F of the surrounding field is maintained constant at 5 ml. Curves are given for four values of illumination E which the dazzle light-source produces at the eyes of the observer. The data represent the average of two observers.

to the direction of propagation of the light from the dazzle-glare source; that is, proportional to

$$\frac{\pi P^2 \cos D}{4}$$

where P is the diameter of the pupil in millimeters and D the angle in degrees the dazzle-glare source is above the line of vision. Therefore,

$$B_1 = 4 \frac{E}{D^2} = E \frac{P^2 \cos D}{C D^2}$$

where C is approximately a constant with a value of 4 as a fair mean of all the data. Likewise, the exponent of D is only ap-

proximately a constant equal to 2. The average equation for visibility-factor is

$$\frac{F + \frac{EP^2 \cos D}{4 D^2}}{\frac{F(f_1 - f)}{f_1}} = 45 (d - .5)^4$$

where all symbols and limits are as previously given. Further

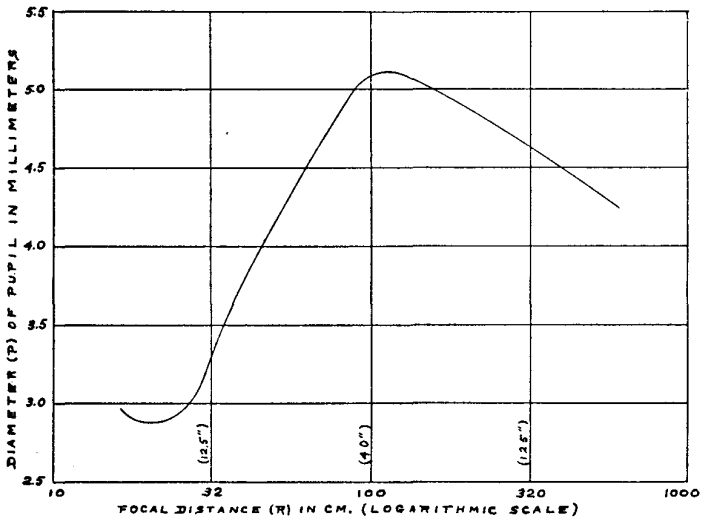


FIG. 13—Showing the variation of the pupil diameter P with the focal distance R for which the eyes are accommodated. The light-source of 5 cm. diameter was placed 30 cm. in front and 13 degrees to the left of the line of vision and it gave an illumination E of 67 mc. at the eyes. The data is the average of two observers.

tests will be required to establish this result more firmly, but there does not seem much room for doubting its general accuracy.

Some study was made of the cause of variation of the diameter of the pupil. When the brightness F of the screen upon which the gaze was fixed was held constant and a dazzle light-source provided a constant illumination E at the eye, it was found that

the diameter of the pupil increased as the angle D between the glare-source and the line of vision was increased. This is illustrated in Fig. 12.

When the illumination is held constant and the distance between the eye and a fixation point is varied it was found that the diameter of the pupil increased gradually from a minimum at a distance of about 20 cm. to a maximum at a distance of about 100 cm. and then decreased for greater distances. This is shown in Fig. 13. It was found that the diameter of the pupil was not materially affected by variations in the visual angle of the test-object.

In order to determine the influence of area and brightness of a diffusing light-source at which an observer looked direct, a test was made by placing a lamp in a diffusing globe at a distance of 117.5 cm. (46.3 in.) in front of an observer and its area was varied. The room in which the test was made was comparatively dark. Denoting the area of the light-source by the solid angle Q which its area subtends at the eye, the brightness of the light-source by B and expressing the diameter P of the pupil in millimeters, we obtained an empirical equation representing the average diameter of the pupils of the eyes of two observers to be

$$P = 5.53 - \log B - .5 \log Q.$$

In this preliminary publication we have purposely avoided comparing our data with that obtained by others. We feel that in such a field as glare and visibility in which there is such uncertainty, it is well to conduct the investigation as independently as possible from unconscious prejudices. However, we should mention the work of Dr. P. G. Nutting, Mr. Ward Harrison and others. In due time we hope to make detailed comparisons. In closing, we wish to express our appreciation of the interest which Mr. Ward Harrison has displayed in the work we are doing in this direction. The illuminating engineers' viewpoint is helpful to those engaged in laboratory work.