PAPERS

THE NEW SCIENCE OF SEEING*

BY M. LUCKIESH** AND F. K. MOSS**

SYNOPSIS:—Seeing is the result of a partnership of lighting and vision. Extensive though incomplete knowledge is available pertaining to the eyes and to the visual sense. The optical profession deals with this partner which by means of lenses, if necessary, is best fitted for its work. Lighting is a relatively new art in whose accomplishments the lighting profession can take justifiable pride. However, relatively little has been accomplished in the development of the partnership of lighting and vision which results in seeing. Since artificial light has become highly controllable in quality, quantity, and distribution, we have the need of and opportunity to develop a new science—seeing. The authors present systematized glimpses of the results of scientific investigations, which aim to show that this new science of seeing is in the making. Upon a foundation of this new science the seeing specialist has an opportunity to develop and to serve the work-world, so that human beings may conserve and utilize their resources to the best advantage of themselves and of civilization.

The long age of *mere* artificial light passed into history with the advent of gas-mantles and electric lamps. The era of *more* light had arrived and interest in illumination was born. Eventually the illuminating engineer appeared and he began to preach the gospel of foot-candles upon a horizontal work-plane. During the present century great strides have been made in the production of artificial light and we now have highly controllable artificial light at a relatively low cost. As a consequence, the possibilities of lighting have been greatly extended and scientific interest has correspondingly deepened.

To those who look at artificial lighting from this viewpoint, a lighting art presents itself which is destined to overflow in all directions those activities commonly known as engineering. This lighting art will be almost as extensive and as complex as human activities. The eyes as doorways of light are the main passage between the complex exterior world and our complex consciousness. Everywhere and in every way in which these doorways of light are used, light is essential. The potentiality of lighting includes

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much more than the physical and engineering aspects. Most of it is founded upon psycho-physiological sciences which in respect to lighting are little appreciated by the many and are being developed by very few.

As we pass through the foot-candle stage, one of the new branches of the future lighting art will be lighting for seeing. However, before it can be evolved with certainty we must build a new science of seeing. There is no more difficult field of research for those of long experience and interest; and for those possessing little acquaintance with the underlying sciences there are pitfalls on every hand. These are the reasons for the scarcity of reliable data and the slow growth of the science. Technique and methods are still in the process of development so that even reliable data of qualified investigators can seldom be intimately compared or correlated.

Helmholz and others left us a heritage of knowledge of the visual organ and sense but relatively little pertaining to lighting and vision. As our studies of lighting and of vision go deeper it becomes obvious that seeing is a partnership of lighting and vision. With modern artificial light controllable in every respect—quality, quantity, distribution, diffusion, direction—we have control of the external partner. Over the internal partner we have no control excepting the application of lenses to sharpen the visual tool and otherwise put it in the best condition. A study of this partnership is necessary for the development of a new science of seeing.

In the limited space of this paper we can do no more than to attempt by means of a few glimpses to convince the lighting specialist that such a science is being developed and that herein lies opportunity to evolve into a seeing specialist which the work-world is in need of. On the one hand, the members of the lighting profession are dealing with lighting and on the other the optical profession are dealing with vision. For the most part these two are separated and are concerning themselves each with one of the partners of seeing. Who will be the seeing specialist of the future; one of these who learns to deal with the partnership or will it be someone else not yet upon the horizon?

In Fig. 1 is a graphical representation of the partnership of vision and lighting. The optician can get the eye in best condition to do its part. The other partner of seeing is at present in the

BALTIMORE TRUST COMPANY

Baltimore and Light Streets, Baltimore, Md.

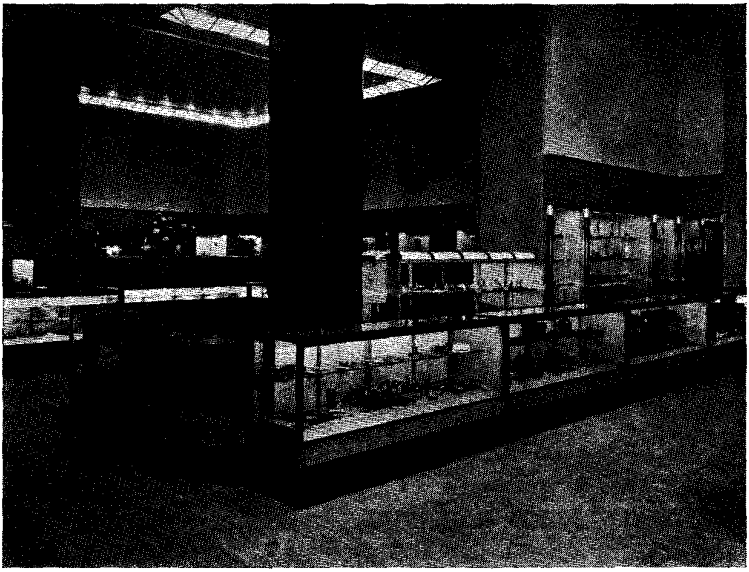
MAIN BANKING ROOM

Taylor & Fisher; Smith & May—Associate Architects

This spacious room, 200 feet long, 80 feet wide, with a 50-foot ceiling, is thoroughly modern in its general style and has a most interesting decorative treatment. The side walls are of "Dovia" stone, the massive columns are of different colors of rare marble, and the ceiling is richly decorated in brilliant polychrome. The floor is a marble mosaic. The wrought iron work of the balcony rails, the windows and writing desks is particularly attractive and exhibits some of the most recent tendencies in design.

There are twenty huge pendant luminaires made by *E. F. Caldwell & Co.* From the illustration these might appear to be the conventional type of bank fixture where round-bulb, frosted Mazda lamps are studded on the rims of metal circles. As a matter of fact this is not the case, and the fixtures represent a distinct step forward in the utilization of light for such an interior. The metal work is very carefully conceived and modern in spirit having a delicacy and lace-like effect that is most pleasing. There are three successively smaller circles of upright sockets, totalling 36, supported at the end of the metal design. Each of these carries a bowl-shaped, dense opal reflector and 40-watt Mazda lamp pointing upward. Thus we have virtually a large multiple unit semi-indirect fixture. The light is effectively sent upward to the highly colored ceiling which should be well illuminated and then, of course, reflected downward. The brightness is of a very low order and the installation is an excellent example of decorative lighting which observes the fundamental principles set forth by the illuminating engineer. Auxiliary lighting is, of course, provided in the areas below the balcony, as well as local illumination for the writing tables.

I. E. S. Committee on Light in Architecture and Decoration.



STEWART & COMPANY

626 Fifth Avenue, New York City

MAIN FLOOR—DEPARTMENT STORE

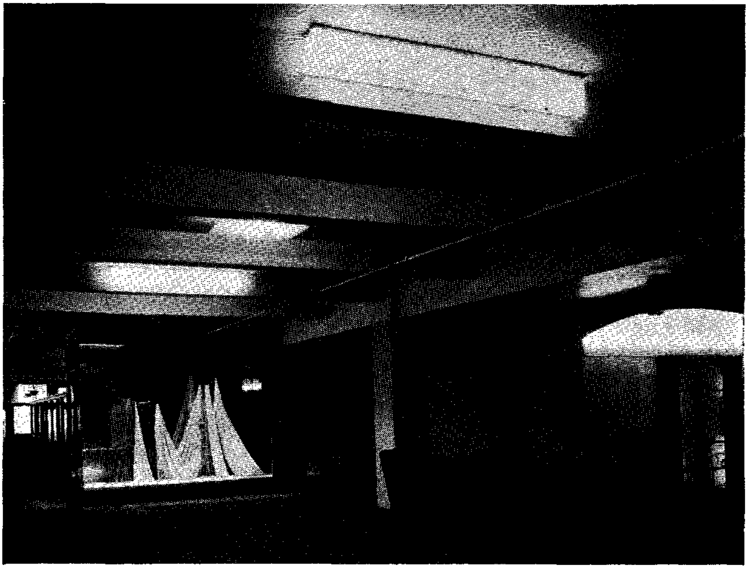
Whitman & Goodman, New York—Architects & Decorators

It would be anticipated that this, the latest of New York's large exclusive shops, would be decorated in a most interesting manner and have lighting in the spirit of the times. The accompanying view shows only one corner of the whole area. The general plan takes the form of a huge cross. At the very center is a special fixture made by *Black & Boyd.* Radiating from this are ceiling boxes of refracting prismatic plates made by the *Holophane Company* and assembled into continuous lines by the *Sunlight Reflector Company.* In the four corners, one of which appears above, similar boxes are arranged in a U shape. The lines of the light boxes throughout practically follow the aisle arrangement. Fifty watt Mazda lamps are used on one-foot centers. Circuits are so arranged that varying degrees of illumination can be obtained. When all lamps are burning the illumination level is in the order of 12 foot-candles. The equipment is so designed that there is not a bad "spotting" effect when only half the lighting is in use.

High level, show-case illumination is obtained with 25-watt tubular Mazda lamps in small trough reflectors. With some of the higher cases the tops are designed to form a bit of luminous decoration.

This example is an excellent indication of the tendency which must grow of combining the modern ideas with scientifically designed equipment and engineering principles, obtaining thereby an effective installation, thoroughly unique and pleasing.

I. E. S. Committee on Light in Architecture and Decoration.



SIDNEY BLUMENTHAL & CO.

1 Park Avenue, New York City

CUSTOMERS ROOM AND DISPLAY FLOOR

Buchman & Kahn, New York—Architects

The reinforced concrete and steel construction of the present-day buildings with the projecting floor trusses has brought about the necessity of conceiving new methods of decorative treatment. There is a sturdiness and mass effect about such an interior which makes the traditional or classical decorative schemes most incongruous. It is positively ridiculous to install, for example, an elaborate decorative fixture of any period in such surroundings. Here the architect has approached the problem with a boldness which is most commendable. He has made no attempt to conceal structural form. On both sides of every third beam he has built a box of diffusing glass approximately 5 feet long, 10 inches wide and 5 inches deep, and in this placed eight 25-watt Mazda lamps. Midway between these boxes a square ceiling box of the same material with eight 25-watt Mazda lamps is held up with a minimum of visible metal work. Each bay is 24 x 24 feet, the ceiling is 11 feet and has two of the rectangular and one of the square boxes effective for its area. The illumination level is slightly over six foot-candles. Several well lighted glass display windows are placed at various locations. *Walter Kantack* designed and manufactured the simple, yet most interesting luminaires.

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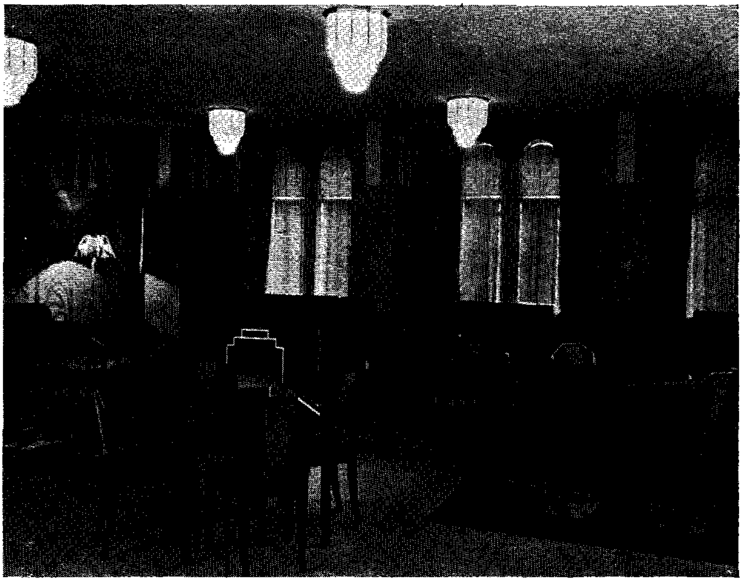


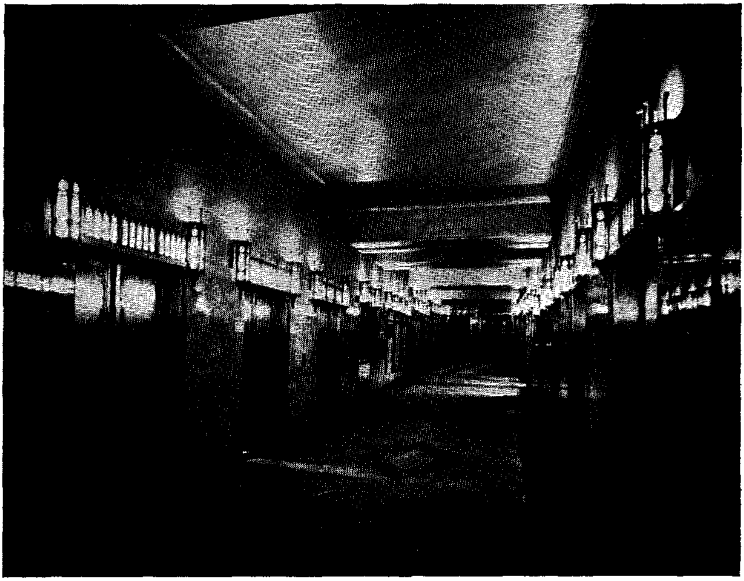
PANHELLENIC BUILDING

3 Mitchell Place, New York City

CARD ROOM

John Mead Howells, New York—Architect

This women's hotel and club house presents throughout one of the best examples of standardized design which with intelligent decoration has been made to present the most charming appearance. The standard loft building type of structure is utilized. Walls and ceilings are left in their rough state, but by the use of carefully chosen colors applied in the modern spirit, have been transformed. A few hangings of modern fabrics relieve any bare effect, and the furniture and floor coverings, also of the new spirit, are interesting and yet most serviceable. The fixtures by *Cox, Nostrand & Gunnison* used throughout are quite inexpensive and yet entirely suitable. The luminaires for each of the rooms are different yet similar in principle and design. In this example they are made of golden tinted, art glass, leaded. There are virtually three cylinders suspended one within the other. The lower scalloped edges of each cylinder are bent inward which gives a flower-like effect. A single 100-watt Mazda lamp is used at each outlet which are on approximately 8-foot centers. The principles of good lighting have been adhered to, there is well diffused general illumination, adequate diffusion to the light, and the glass is so chosen that the fixture is not bright.



PUBLIC SERVICE BUILDING

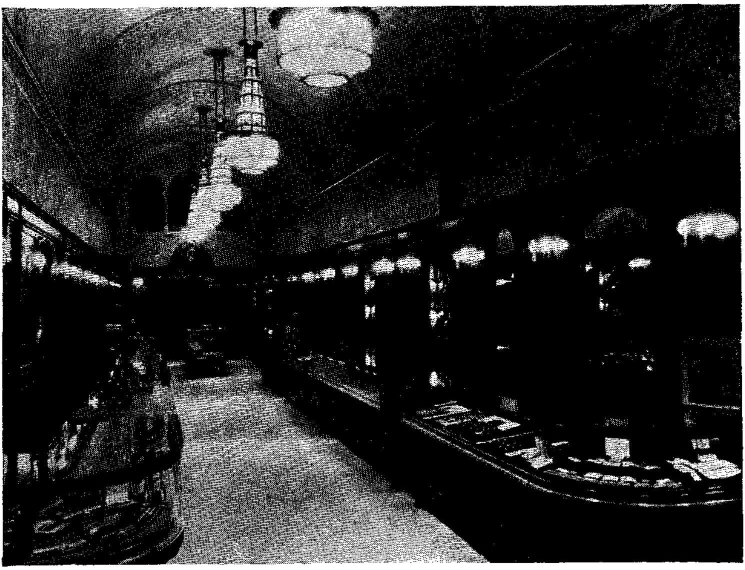
Franklin, Broad and Batterymarch Streets, Boston, Mass.

ELEVATOR CORRIDOR

Harold Field Kellogg, Boston—Architect

Over each bronze elevator door is constructed a bronze grille 15 inches high with special alabaster glass panels, the ornamentation of the metal work being a continuation of that of the doorway. Twenty-five watt amber colored Mazda lamps are used on 6 inch centers. *The Lord Electric Company* are the manufacturers. There is a total of 400 lamps for the corridor which is 120 feet long and 20 feet wide. The illumination level is two foot-candles. The lower walls are amber colored marble, the upper walls and ceiling are of plaster tinted in harmonizing colors. The building throughout is unusually attractive. Its exterior conforms to the newer school of design. Brick construction is employed throughout. Thirty different colors are used, so graded that the surface changes from a deep heather brown near the base of the building to slowly fading lighter colors attaining a light colored buff finish at the peak of the structure.

Certainly one receives a most pleasant impression as he enters the building and the lighting arrangement is responsible for this. A soft warm glow floods the entire area and the light emanates from the very structure itself. A treatment such as this is far more ingenious than the installation of extraneous equipment solely for the purpose of furnishing light.



ABELSONS, INC.

855 Broad Street, Newark, N. J.

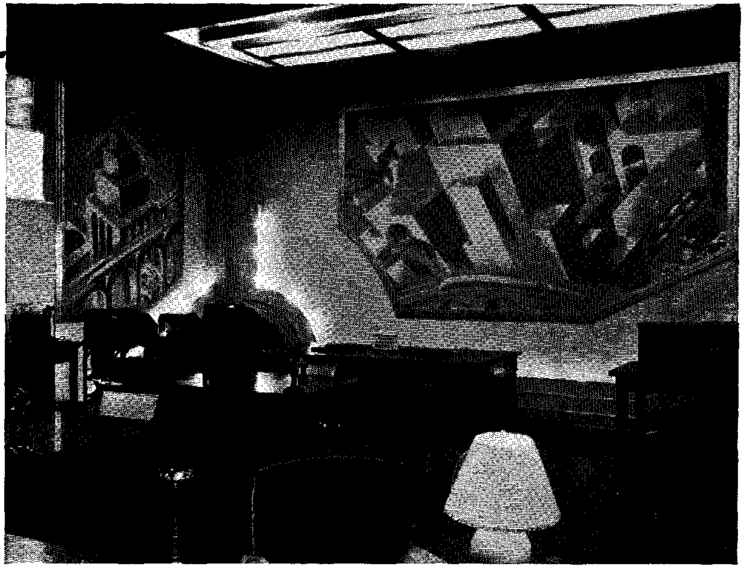
JEWELRY STORE

I. Rubenstein, New York—Architect

The jewelry store catering to a certain class of trade finds it desirable to provide a very bright interior and, unfortunately, this effect is often accompanied by extremely glaring conditions. Here, however, plenty of light is provided everywhere, yet the system is so planned as to make an attractive ensemble. The lower part of the side walls is filled with richly paneled mirrors and woodwork which matches the show-cases. The wall above this and the vaulted ceiling is decorated in a light green tint with some contrasting relief work.

Six pendant luminaires of a most original design are used. These are made of sections of diffusing glass with ornamental metal applied decorations. A two-rod support is used. Within the body of the fixture are used eight 75-watt Mazda lamps to make the whole fixture luminous. In the upper section is a chromium plated reflector with a 200-watt Mazda lamp for totally indirect lighting. In the bottom section of each is a 1000-watt Mazda lamp in a bowl-shaped chromium plated reflector for direct lighting. Metal louvers are placed over the opening in such a manner as to prevent the large lamp being visible except when looking directly upward. *The Kaylite Manufacturing Co.* designed and constructed the luminaires.

The store is 16 feet wide by 75 feet long and the ceiling has a maximum height of 20 feet. The bottom of the fixtures are 10 feet above the floor and outlets are on 10-ft. centers. An illumination level of 100 foot-candles is found directly beneath the units so that one may examine the merchandise with facility. On the tops of the show-cases, which are themselves also lighted, is found approximately 40 foot-candles. There is a sufficient amount of indirect and diffused light to prevent annoying contrasts.



NEW YORK TELEPHONE COMPANY

89 Willoughby Street, Brooklyn, N. Y.

RECEPTION AND DISPLAY ROOM

Designed by Company Engineers

In this unique interior the latest types of commercial and special telephone equipment are displayed and the setting provided is certainly appropriate. The art of communication is developing with extreme rapidity and it is logical that the general atmosphere of the room should emphasize the future and progress. As will be seen, murals of unusual contours depict the skyscraper cities to come. The lighting is decidedly novel. Instead of the conventional wainscoting there are provided light boxes which follow the peculiar outlines of the murals. These are about 3 inches in depth, and 25-watt Mazda lamps on 12-inch centers are concealed within. The box is painted white inside and a frosted glass cover-plate is used. By this means the wall surfaces are made reasonably luminous.

Overhead there are two rectangular ceiling boxes approximately 5 x 20 feet. These are close to the beams and are made of wood, painted green harmonizing with the general decorative scheme of the room, and panels of frosted glass. As will be noted, a step-like arrangement of the frames is employed. In each box are thirty 100-watt Mazda lamps.

On one of the side-wall pilasters seen at the left is another luminous box arrangement with seven 25-watt Mazda lamps. The room is approximately 28 x 35 feet with a 14-foot ceiling. A total of 8200 watts produces an illumination level of 30 foot-candles on the horizontal plane and approximately 20 foot-candles on the side-wall decorations. The lighting equipment was constructed entirely in the shop of the company.

One side of the room is constructed entirely of plate glass so that the display is visible from the street. The attractive lighting and clever decorative scheme combine to make a most appealing picture.

CIVIC OPERA HOUSE

Wacker Drive and Madison Street, Chicago

GRAND FOYER

Graham, Anderson, Probst & White, Chicago—Architects

This beautiful entrance with the grand staircase on the left is done in the French Renaissance style modified and modernized. Even the double piers which support the cornice and ceiling have their flutings in a modern manner. The general tone is a soft buff with a suggestion of gold in the capitols, and the ceiling and cornice are brilliant red and gold. The luminaires by *Sterling Bronze Company* are well designed to take advantage of the modern light sources and yet thoroughly harmonious with the decorative treatment. The architect has not handicapped the lamps by attempting to simulate archaic types of fixtures. They are of sectional glass construction with applied filigree work in metal. The mask, always associated with the theatre, is incorporated and gives a distinctive touch.

Instead of using the conventional torchieres on the piers this basic form has been modernized and the massive metal support surmounted by three concentric cones of diffusing glass. In the background above the stair will be noted a ceiling lunette, and above the stairs leading to the men's smoking room a touch of brilliant lighting. This is in the form of a huge peacock with luminous tail feathers of frosted glass.

This area is 82 ft. wide, 28 ft. long with a ceiling of 28 ft. In the three pendant luminaires are used fifty-six 50-watt Mazda lamps in each, and in each of the twelve side-wall units twelve 40-watt and four 25-watt tubular Mazda lamps.

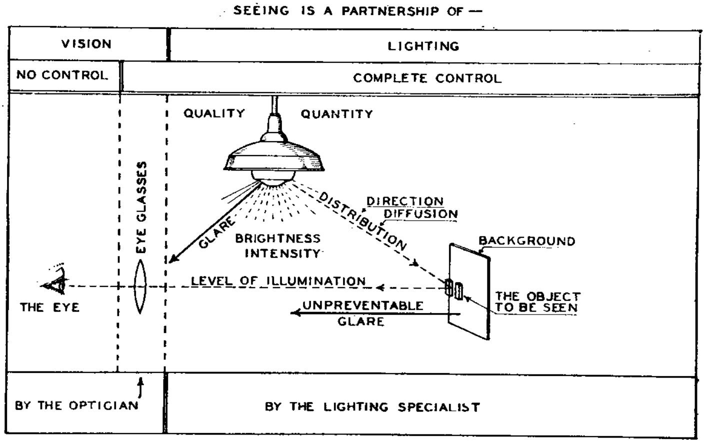


FIG. 1.

hands of the lighting specialist. The only inherent property of light is quality or spectral character. The most obvious factor in lighting is quantity or foot-candles. Even with the light well diffused from an approved fixture a certain degree of reduced visibility is due to the so-called glare from the light reaching the eye directly from the lighting unit. Light may be properly distributed—directed and diffused—upon the object to be seen and a proper level of illumination may be supplied. Backgrounds are usually ignored but they can have a great influence upon the visibility of an object. The light from the object and surroundings is not usually recognized as glare but it does reduce visibility. It is unpreventable glare, usually of such mild form as to be ignored, but it is inherently present under the best lighting conditions. It tends to close the pupil and to decrease retinal sensibility. The net result of more light at the object and better lighting of it is improved seeing notwithstanding the unpreventable glare. In fact, seeing is a result of all these major factors and many minor ones. The best combination of the factors produces the best seeing.

Certainly, level of illumination is highly important but it is far from all-important. As lighting for seeing develops, the foot-candle decreases in value as a description of lighting conditions. At the present time it is interesting to note that the few foot-candles which represent the average levels in artificial lighting are only one-thousandth of the levels of illumination outdoors under which human eyes developed. Coincident with coming indoors to greatly restricted levels of illumination, the seriousness of the work which human eyes were called upon to do greatly increased. Is not this the clue to the general defectiveness and weaknesses of vision?

The foot-candle is only a measure of intensity of illumination. It is not a measure of seeing. As an influence upon seeing its value is not fixed; for, other conditions remaining the same, the effectiveness of a foot-candle, as a direct aid to seeing, diminishes as the level of illumination increases. To double our ability to see it is necessary to increase the level of illumination many times if other factors are not altered. The effectiveness of an additional foot-candle depends upon at least three primary factors: (1) the visual difficulty of the work which the eyes must perform; (2) the manner in which the additional light is used; and (3) the level of illumination to which it is added. But it is also possible to alter quality, direction, diffusion, and distribution of light, with a resulting increase in the ability to see in many cases.

The measurement of seeing is not a simple matter. Vision is more or less flexible, perhaps in order that it may operate over a very wide range of conditions. What the new science of seeing is concerned with eventually is the best combination of conditions which enables us to see most easily, most accurately, most safely, most quickly and most comfortably. It is concerned eventually with the greatest productiveness and with complete conservation of vision and of other human resources which are drained through the process of seeing.

Certain optical methods of measuring vision are indicated in Fig. 2. Actually, those in general use measure visual acuity or the threshold size or separation of objects. As a measure of size the seeing specialist must begin to use the angle subtended at the eye by an object or by the distance between adjacent objects or details. Size becomes a matter of subtended angle of critical details. To give some idea of this unit of size we have shown in Fig. 2 the visual angle in minutes corresponding to three sizes of object at the normal reading distance of fourteen inches. In the early years of our work we found visual acuity and the usual test-objects inadequate for the study of seeing. After devising and

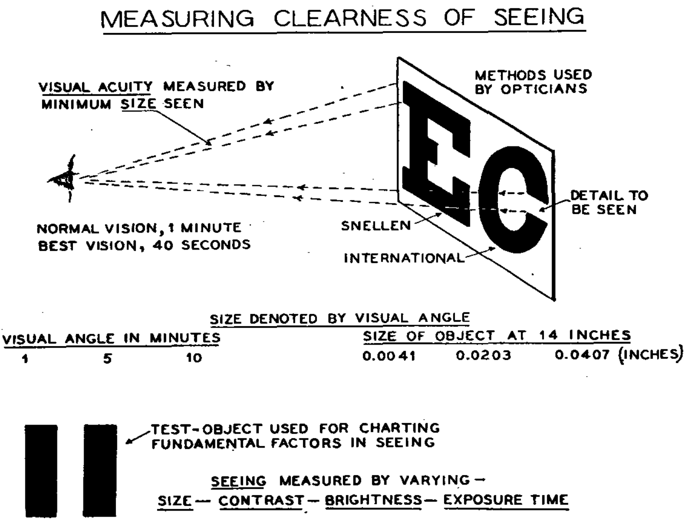


FIG. 2.

using various simple test-objects, we developed the one shown in the lower left of Fig. 2 and have used it in a series of investigations conducted continuously for many years. Eliminating color from consideration, we began a systematic study of the fundamental variables of the object—size, contrast, brightness, and time of exposure. Science is founded upon measurements and the science of seeing is no exception.

Vision has the peculiarity of being a variable tool. When we get down to fine measurements we cannot find a sharp boundary between seeing and not seeing an object. Therefore, years ago we were confronted with the task of determining clearness of seeing. When the conditions are such that it is difficult to see a given object, we may see it at one moment and may be unable to see it the next moment. Furthermore, to be certain that one does recognize a test-object it is necessary to alter its position. In this case we rotate the object in its own plane. Another refinement which is approved in such researches is to expose the object to vision, for a given interval of time rather than to expose it for indiscriminate intervals.

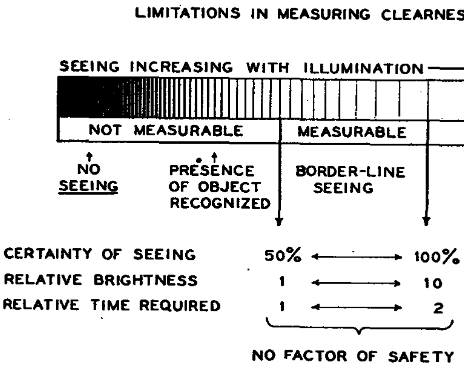


FIG. 3.

In Fig. 3 we have attempted to construct a simple diagram which illustrates the limitations in measuring the clearness of seeing and also some general results. Our test-object may be assumed to be used under a great range of levels of illumination from zero foot-candles on the left to a very high level on the right. Assuming that this test-object is of a certain size and contrast, it cannot be seen until it and its background are illuminated to a certain level. We then enter a region of border-line seeing which is a wide strip and not a narrow border-line as boundaries usually are. What shall we take as a measure of seeing? Certainly not the conditions under which it can be seen only one-half the total times it is presented or looked at. Shall it be the point of 100 per cent certainty? If so, it takes ten times the intensity of illumination or twice the time for 100 per cent certainty of seeing as for 50 per cent certainty. This region of border-line seeing is the only measurable region. Obviously, no measurements of seeing can be obtained when one cannot see the object. Likewise, after the lighting conditions have reached the point where one can see the object every time it is presented to the eyes, no measurements of this kind can be made. However, one can not say that seeing does not become easier if the intensity of illumination is still further increased. Measurements of eye-fatigue, ease of seeing, output of visual effort, etc., which have generally defined investigation as yet are sorely needed in order to reveal the relation of lighting to the conservation of eyesight and human energy. Some data already point in this direction.

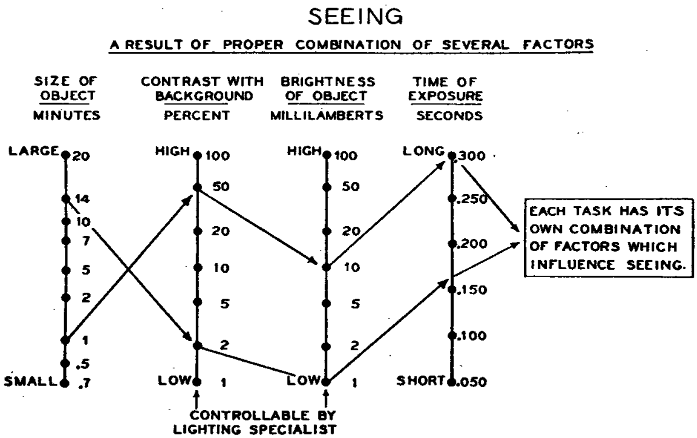


FIG. 4.

In our work we usually assume 50 per cent certainty of seeing to be the border-line of seeing.

Our ability to see an object depends upon at least four primary variables—size, contrast, brightness, time of exposure. Two visual tasks may be equally difficult when each of these factors differs as indicated in Fig. 4. *Size* is measured in visual angle—minutes subtended by the object at the eye. *Contrast* is defined as the ratio of the brightness-difference between the object and its background to the brightness of the background and for simplicity is expressed as per cent contrast. A perfectly black object on a perfectly white background has a contrast of 100 per cent. *Brightness* usually means the brightness of the background because the object to be seen is usually small and actually the background is a part of the thing seen. If the objects or details cover an appreciable part of the background, such as a page of printed matter, the brightness is the average brightness.

The size of an object just visible depends upon all the factors of light and of lighting. Assuming every factor constant excepting intensity of illumination, the minimum size of an object just visible, or rather the minimum spacing between critical details which can just be resolved by the average normal eye at a distance of fourteen inches, is as follows:

Foot-candles	1	10	100
Size of object in inches	0.00467	0.00357	0.00264
Relative size of object	100	76	57
Relative visual acuity	100	131	177

It is seen that approximately the same increase in visual acuity is obtained by increasing the level of illumination from 1 to 10 foot-candles as for an increase from 10 to 100 foot-candles. These results apply to border-line seeing at which seeing is only 50 per cent certain.

In passing, let us take a glimpse of the relation of the time required to see an object and of the certainty of seeing. From one investigation involving 60,000 observations the results obtained were as follows:

Per cent certainty of seeing	100	80	50
Relative time required to see object	100	63	48

In analyzing any visual task we have to consider the characteristics of the light, lighting, visual object, and of vision. The only physical characteristic of light is its spectral character. Color is a psycho-physiological characteristic sometimes important in a way differing from that of spectral character. The characteristics of the visual object are always size, contrast, brightness, and sometimes exposure-time, color, and spectral reflection or transmission Fundamental characteristics of vision are retinal sensibility to size, brightness, brightness-difference, and time. Some of these characteristics are influenced by light or lighting and some are born of these. The actual size of an object is fixed but its apparent size depends upon such factors as shadow, highlight, background, and brightness.

Some of the characteristics of the eyes—the visual tool—are fixed but some are influenced by lighting. Among the latter are pupil-size, which varies with the lighting, brightness-level, and brightness ditsribution. Pupil-size in turn influences definition, resolving power, adaptation, and brightness of retinal image.

In Fig. 5 are presented the relations between brightness and contrast for our parallel-bar test-object of various sizes in minutes visual angle. The brightness is expressed in millilamberts. A brightness of one millilambert is that of a colorless surface of 80 per cent reflection-factor illuminated to an intensity of 1.16 foot-

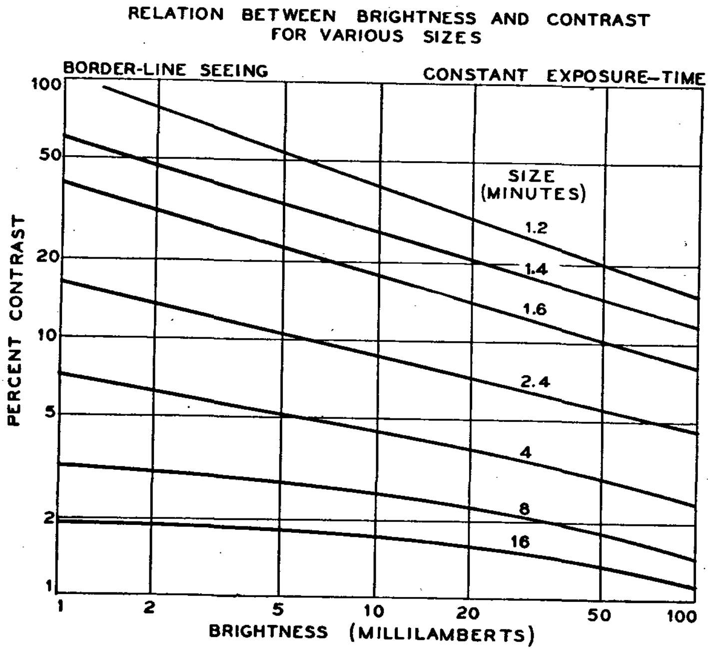


FIG. 5.

candles. It is also the brightness of a colorless surface of 8 per cent reflection-factor illuminated to an intensity of 11.6 foot-candles. Therefore, the scale of brightness in Fig. 5 is approximately a scale of foot-candles for a good white background against which the test-object is seen. This scale multiplied by ten becomes a foot-candle scale for a background of 8 per cent reflection-factor. It is seen that for a given size of test-object the contrast necessary for the object to be visible becomes smaller as the level of brightness (or illumination for the same background) increases. This minimal contrast decreases more rapidly for the smaller objects than for the larger ones.

In Fig. 6 the relations between size and brightness for various contrasts are shown. As the brightness-level increases the minimal size of a barely perceptible object decreases.

In Fig. 7 the same data as in Figs. 5 and 6 are presented in another manner. Here we have the relation between size and contrast of barely perceptible objects for three brightness-levels. As

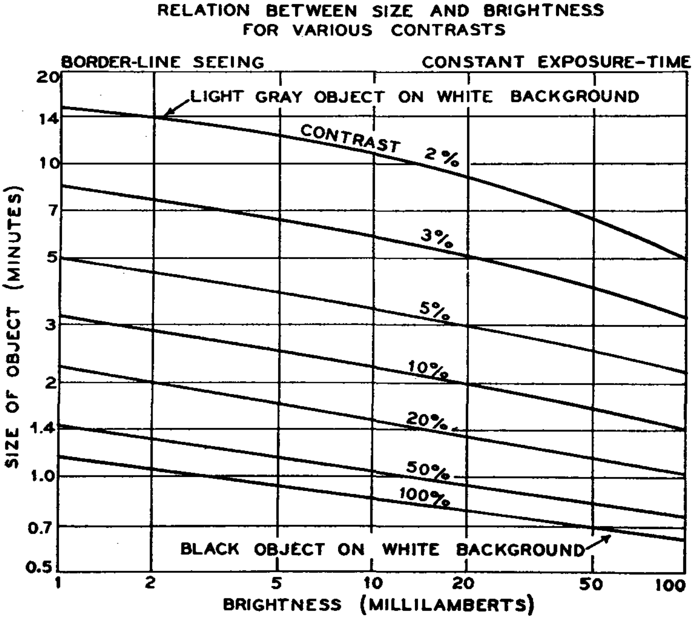


FIG. 6.

the brightness-level decreases either the minimal size or minimal contrast or both must be increased if the object is to become visible again. For example, our test-object of 2.5 minutes visual angle must have 5 per cent contrast to be visible at a brightness-level of 100 millilamberts. If the brightness-level is only one millilambert, about 20 per cent contrast is necessary to render it visible. Contrast is a very important factor in seeing.

One of the first steps which the lighting specialist should take toward becoming a seeing specialist is to interpret foot-candle-levels into brightness-levels. In a previous publication[1] one of the authors adopted a new procedure in presenting foot-candle-scales in graphic representations of data. By indicating the reflection-factor the foot-candle-scale becomes a brightness-scale. The lower scale is in foot-candles upon a surface of 80 per cent reflection-factor and the upper one in foot-candles upon a surface of 8 per cent reflection-factor. The two scales thus are identical

[1] *Light and Work*, by M. Luckiesh, 1924, D. Van Nostrand Co., New York.

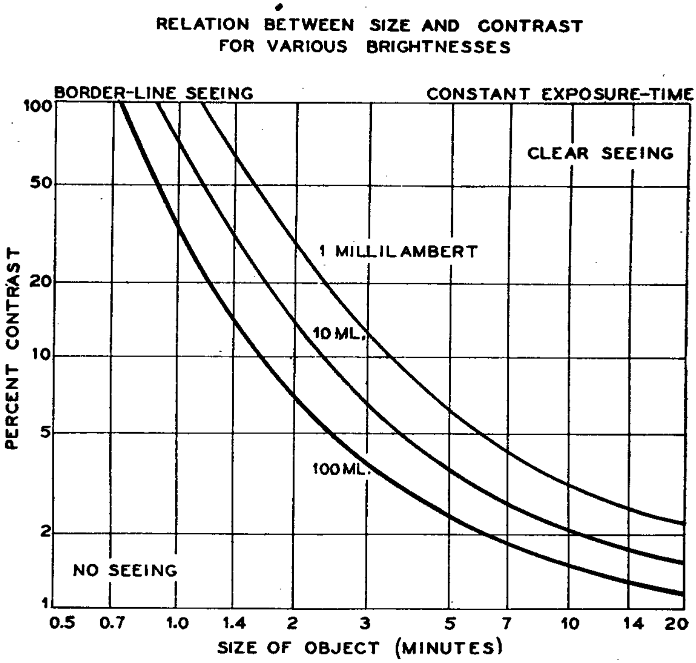


FIG. 7.

as brightness-scales but the values of foot-candles on the upper scale are *ten times as great* as those on the lower. These two reflection-factors include most of the range met in the practice of lighting and this method of plotting data certainly emphasizes a glaring fault of the foot-candle as a measure of lighting for seeing.

This is well illustrated in Fig. 8 in which the relation of brightness-level and the precision of seeing is presented. The visual task was primarily the setting of the lower pointer so that its point was directly below the upper one. These were seen against a background of 80 per cent reflection-factor. The decrease in error of setting with increase in brightness-level is shown for two conditions: (1) when the surroundings outside the white background were not illuminated, and (2) when the surroundings were illuminated to the same brightness as the background of the ob-

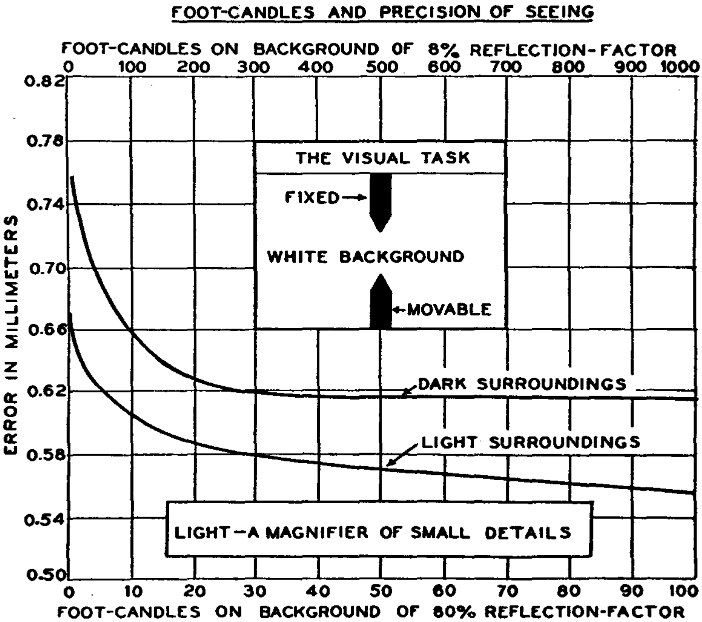


Fig. 8.

ject. If these results are interpreted narrowly one might conclude that in the case of the usual bright surroundings most of the advantage of more light on the background was obtained at 30 foot-candles. However, consider steel scales and the slight contrast between the rulings and the background, and also the low reflection-factor of the background. If the reflection-factor of the background (Fig. 8) had been 8 per cent—a dark gray—the foregoing interpretation placed upon 30 foot-candles would apply to 300 foot-candles (upper scale). It will be noted that accuracy continued to increase as far as we carried the investigation. It was still increasing at 100 foot-candles on a white background. Besides this increase, we believe there are other advantages which have defied measurement. Interpreting such data as presented in Fig. 8 in terms of general foot-candle practice we must conclude that lighting for relatively easy visual tasks is generally inadequate and that, for the more difficult ones, where details, contrasts, and reflection-factors are small, the present levels of illumination

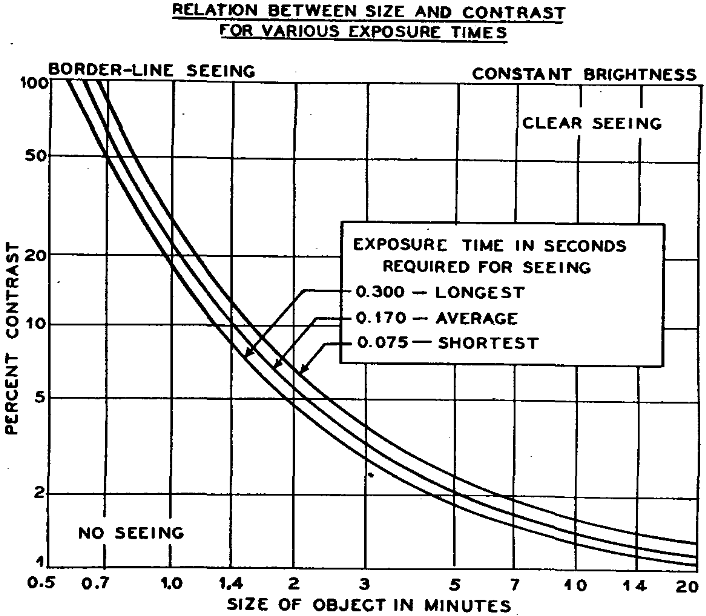


FIG. 9.

are very low. These considerations give us courage to recommend levels of hundreds of foot-candles of proper quality and distribution. In the present stage of economics it has led us to the conclusion that highly specialized localized lighting[2] superposed upon general lighting is necessary for the development of lighting for best seeing.

In Fig. 9 are presented the relations between size and contrast of our test-object for various exposure-times. Although in certain cases speed of vision is important it is seen that usually it is less important than size, contrast, and brightness-level. The reaction-time of human beings has certain inherent limitations beyond which it cannot be increased.

Now let us take a few glimpses of the visual tool as influenced by lighting. The pupil of the eye is quite temperamental and it is difficult to make measurements of it. However, Fig. 10 represents fairly well the variation of the size of the pupils when the eyes

[2] *General Lighting Plus,* by M. Luckiesh; TRANS. I. E. S., 24, 1929, 233.

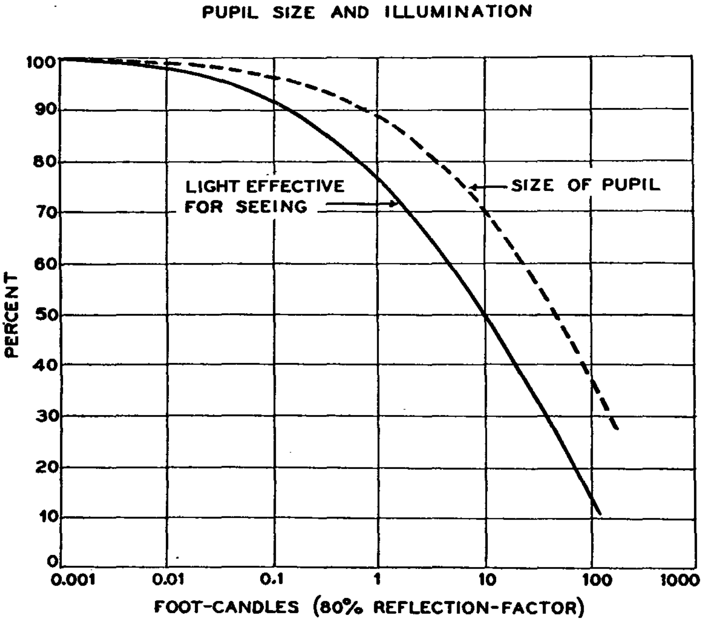


FIG. 10.

are exposed to various brightness-levels. As the brightness-level of the work increases, the diameter of the pupil decreases as indicated by the broken line. The brightness of the retinal image diminishes in proportion to the area of the pupil or the square of the diameter. As the brightness-level increases, the light effective for seeing diminishes as indicated by solid line. Although under the best lighting conditions the pupil-size decreases with increase in brightness-level, one of the aims in lighting for seeing should be to eliminate conditions, such as preventable glare, which reduce pupil-size and consequently decrease the amount of light effective for seeing.

Besides this important factor, there are two other purely optical one which oppose each other. As the pupil decreases in size, the *resolving-power* of the eye decreases, and the *definition* of the retinal image increases. In Fig. 11 it is seen that the relative visual acuity remains practically constant over a range of pupillary diameters from two millimeters to five millimeters. This is shown for two extreme conditions. The full line represents the relation

PUPIL SIZE AND VISUAL ACUITY

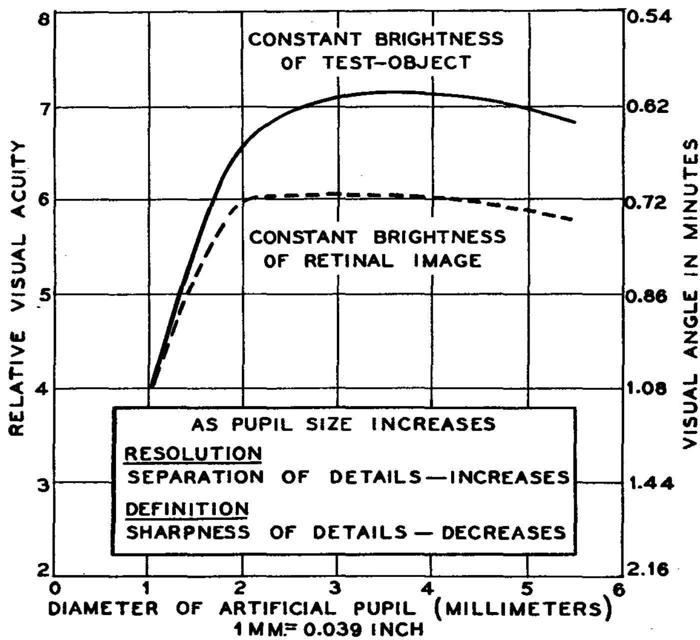


FIG. 11.

between visual acuity and size of pupil (artificial apertures placed close to the eye) for a constant brightness of test-objects. The broken line represents the same relation, excepting that the brightness of the retinal image was maintained constant by decreasing the brightness of the test-object in amount corresponding to the increase in area of the artificial pupil from one millimeter diameter upward. The actual minimal size of the object visible under the conditions of the investigation is shown on the right-hand vertical scale. These data indicate that, throughout the usual range of pupillary size, the sharpness of the visual tool is not appreciably influenced by pupil-size. However, the effect of brightness of retinal image is important as seen by comparing the two curves. Apparently, after the pupillary diameter decreases below two millimeters the disadvantage of decreasing resolving power is of appreciably more influence than the advantage of increasing defi-

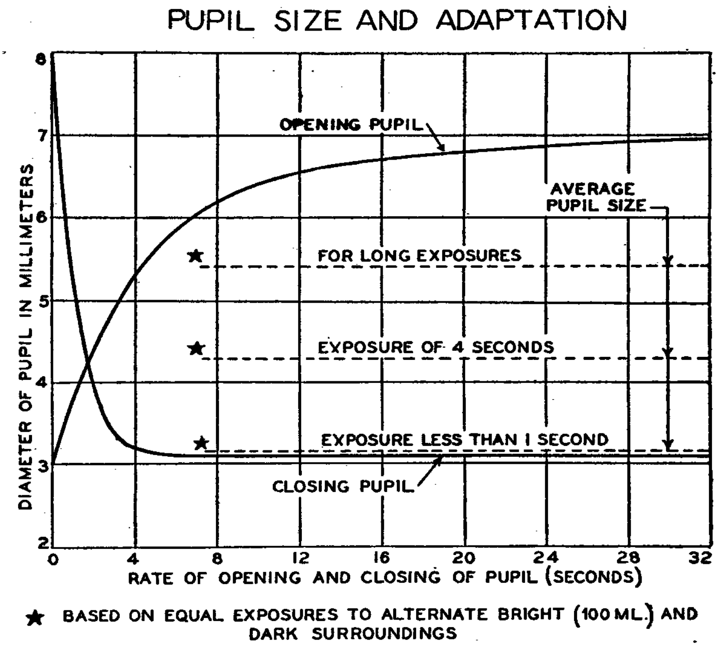


FIG. 12.

nition of retinal image. On beginning with a pupil-size of one millimeter, the advantage of increasing resolving power as the pupil-size increases is greater than the disadvantage of decreasing definition of the retinal image. There may be other factors entering very markedly at this stage but we are not certain of the importance of any such factors.

Certain involuntary adjustments take place in the eyes whenever the brightness of the visual field is altered. The pupil requires about as many *minutes* to open to its maximum diameter as it does *seconds* to close to its minimum diameter. In Fig. 12 it is seen that closing takes place rapidly and that opening is more gradual. In addition to these facts we have shown by the broken horizontal lines the pupil-size when the eyes are alternately directed upon dark and bright surroundings (100 millilamberts) respectively. When the eyes rest less than one second on each surface respectively the average pupil-size is about the minimum. As the period of exposure to each surface increases, the average pupil-size in-

VISUAL WORK UNDER ASSORTED ILLUMINATIONS

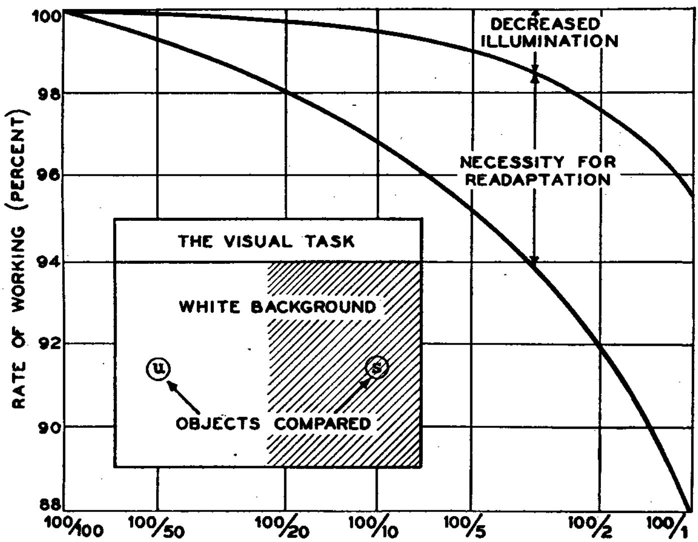


FIG. 13.

creases. These data will bear some study because they throw light upon those conditions where a worker must look back and forth from darker to brighter areas—a condition in many operations.

In Fig. 13 are the results of a series of investigations of this condition. The two fields to which the eyes were alternately exposed were of equal reflection-factor but the ratio of foot-candles upon each varied from 100/100 to 100/1. The observer varied the letters in the two apertures, and his task was to recognize the coincidences, that is, those times when both letters were alike. He recorded these by means of a key in one hand and changed both letters simultaneously by operating a key in the other hand. He was to work at the best rate which was conducive to accuracy. We had an automatic check upon quantity and accuracy of work done. As the ratio of the brightnesses of the two fields increased from 100/100 to 100/1 the rate of working or the production of the individual decreased. The lower curve is the average rate of working for a number of individuals. The upper curve represents the decrease in rate of working due to decreased brightness of one of the test-objects or to decreased average brightness-level. The difference between these two curves represents loss of production due to the time necessary for the eyes to partially become adapted each time they look from one surface to another. Furthermore, there is a very obvious eye-fatigue which, with its results, still defies measurement. These data are interesting in connection with Fig. 12 and, even without considering eye-fatigue, eye-strain, and wasted energy, indicate the disadvantage of compelling the eyes to look rapidly from one field to another of appreciable difference in brightness.

The deleterious effects of glare are well recognized by lighting specialists and much fundamental data is available. However, we have completed a systematic study relating this factor with our investigation of the fundamental factors of vision. The technique used in obtaining the data represented in Fig. 7 was repeated with many observers over the course of about one year excepting that a glare-source (a 100-watt inside-frosted tungsten-filament lamp) was introduced into the visual field at various angles with the line of vision. This glare-source was always at such a distance regardless of its angular position to provide an illumination intensity of five foot-candles at the eyes of the observer. The full lines in Fig. 14 are the same as those in Fig. 7 and represent the relationship of size, contrast and brightness of test-object with no glare-source in the visual field. These relations for three levels of brightness are presented. As the glare-source begins to appear in the outer portion of the visual field, visibility of the test-object decreases. It must have a greater size or contrast in order to be visible. The shaded area in each case represents the loss in visibility when the glare-source is within five degrees of the line of vision for three levels of brightness.

This loss is shown in Fig. 15 in terms of wasted light. All conditions remaining constant excepting the angular position of the glare-source, the decrease in visibility is equivalent to a decrease in the level of illumination of the test-object. Assuming the intensity of illumination to be 100 per cent when the glare-source was absent, the effective intensity of illumination decreases to 58 per cent when the glare-source is 40 degrees above the horizontal line of vision. The effective foot-candles continue to decrease as this angle decreases. In other words, the wasted light, when the

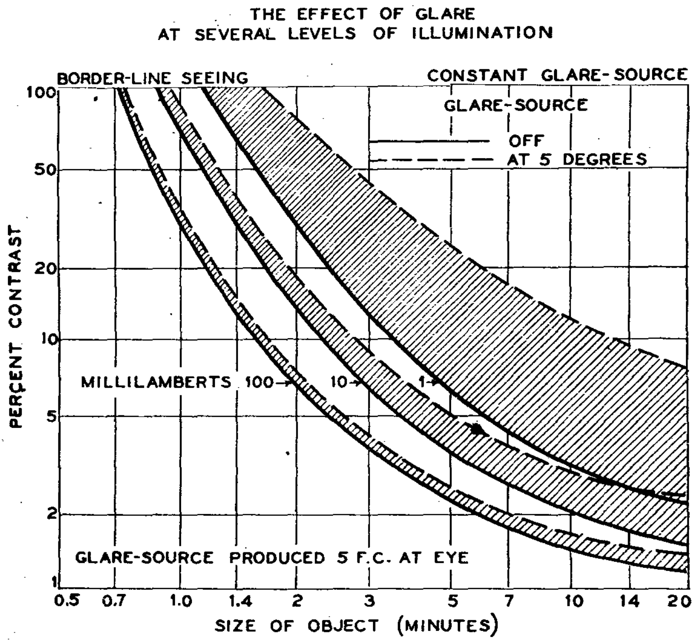

THE EFFECT OF GLARE
AT SEVERAL LEVELS OF ILLUMINATION
BORDER-LINE SEEING
CONSTANT GLARE-SOURCE
GLARE-SOURCE
OFF
AT 5 DEGREES
PERCENT CONTRAST
100
50
20
10
5
2
1
MILLILAMBERTS 100→ 10→ 1→
GLARE-SOURCE PRODUCED 5 F.C. AT EYE
0.5 0.7 1.0 1.4 2 3 5 7 10 14 20
SIZE OF OBJECT (MINUTES)

FIG. 14.

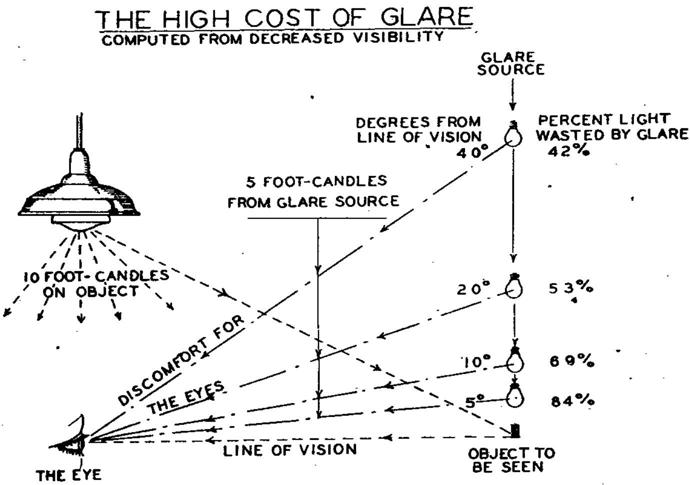

THE HIGH COST OF GLARE
COMPUTED FROM DECREASED VISIBILITY
GLARE SOURCE
DEGREES FROM LINE OF VISION
PERCENT LIGHT WASTED BY GLARE
40° 42%
20° 53%
10° 69%
5° 84%
5 FOOT-CANDLES FROM GLARE SOURCE
10 FOOT-CANDLES ON OBJECT
DISCOMFORT FOR THE EYES
LINE OF VISION
THE EYE
OBJECT TO BE SEEN

FIG. 15.

TABLE I

LIGHTING AND SEEING
RELATION DETERMINED UNDER IDEAL LABORATORY CONDITIONS

FOOT-CANDLES	RELATIVE IMPROVEMENT IN SEEING: SPEED OF VISION	SPEED OF READING	VISUAL ACUITY	ACCURACY OF VISION	AVERAGE RESULTS
1	46	68	72	93	70
5	100	100	100	100	100
10	125	108	108	103	111
15	145	111	110	104	118
20	153	113	112	105	121
30	153	114	113	107	122
40	153	114	114	108	122

THE FOOT-CANDLE IS ONLY ONE ELEMENT OF LIGHTING

glare-source is at an angle of 40 degrees, is 42 per cent. This wasted light increases to 84 per cent when the glare-source is at an angle of five degrees with the line of vision. Viewed in this manner glare is indeed costly; but we are also quite certain that there are other unmeasured losses. Certainly it is discomforting and fatiguing. Possibly it contributes toward permanent injury of the visual tool.

Table I is a summary of some of the investigations we have made in addition to the systematic studies of seeing. All these were conducted with *black test-objects on a white background.* In fact, all conditions for seeing were *ideal.* One who narrowly interprets such data would conclude that no additional benefit accrues from increases in intensity of illumination above 20 or 30 foot-candles. In fact, such conclusions are very prevalent. But if one considers that most visual tasks do not have these maximal contrasts, that most backgrounds or surfaces have reflection-factors considerably below that of white, that experimental conditions are usually free from distractions common to work-conditions, and that such measurements as those presented in Table I do not include measurements of eye-strain, eye-fatigue, wasted energy and general wear and tear, one begins to see that much higher levels of illumination are necessary for the best work-conditions. Furthermore, one begins to suspect that by the act of coming indoors and building an artificial world of his own, man cannot necessarily escape the indelible stamp of ages of outdoor-

TABLE II

PREVALENCE OF DEFECTIVE VISION

BY GROUPS:

	PERCENT DEFECTIVE	PERCENT CORRECTED	PERCENT UNCORRECTED
PUBLIC SCHOOLS	22	13	9
COLLEGES	40	18	22
INDUSTRIES	44	19	25

BY AGES

AGE	UNDER 20	30	40	50	60	OVER 60
PERCENT DEFECTIVE	23	39	48	71	82	95

lighting environment. Perhaps his eyes and his being need the intensities of illumination equivalent to those hundreds of foot-candles outdoors under which they evolved.

Now let us look into a condition of eye-defectiveness which is serious and almost appalling. A condensed summary is given in Table II of nearly one million human beings. Why are the eyes of young people so defective? Why do eyes become more defective with age? Does improper and inadequate lighting contribute toward this increase in defectiveness with increasing age? Generally our organs, our arms, and our legs develop properly under normal conditions. The human race came indoors yesterday and coincidentally greatly restricted the quantity of light and greatly increased the seriousness of visual activities. There is much unknown in regard to the deleterious effects of inadequate and improper lighting upon human eyes and other human machinery. However, from the knowledge we already possess it appears that the new indoor civilization needs very badly a new science of seeing upon which a new art of lighting for seeing can be developed.

If space permitted we could present many glimpses of the value of good lighting in conserving vision. However, we will present

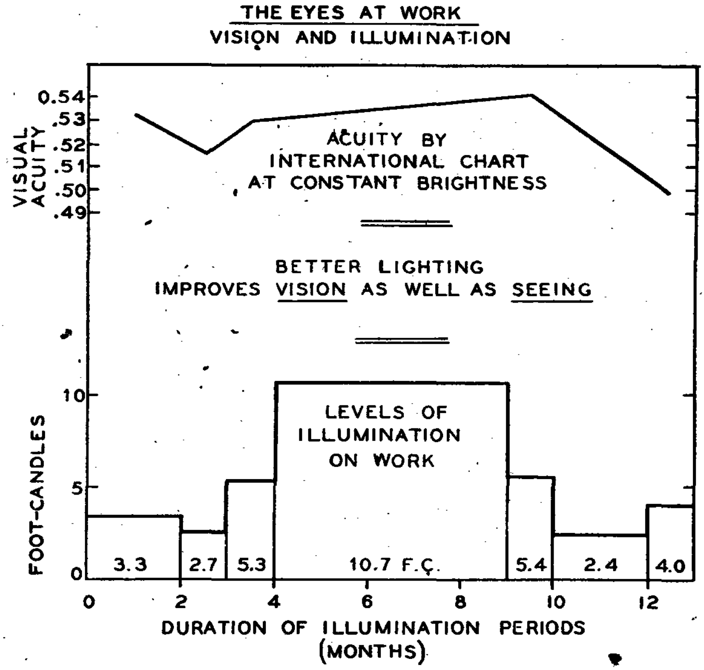


FIG. 16.

only one practical case which seems to provide some evidence in this direction. From the work done by Dr. J. E. Ives[3] and others, we find the interesting relationship shown in Fig. 16. The sorting of mail provided a fairly constant and rather difficult visual task. Among other records made was that of visual acuity of the eyes of the workers. The lower part of the diagram shows the duration and the succession of certain periods of investigation and the foot-candles under which the workers sorted mail. The irregular line at the top indicates the average visual acuity of the workers at certain periods during this series of investigations. It will be noted that an increase in level of illumination produced an improvement in the ability of the eyes to discriminate fine detail. *The measurements of visual acuity were made under constant conditions independent of the work-conditions.* The change in visual acuity noticeably lagged behind the change in foot-candles. Apparently

[3] *Studies in Illumination,* Public Health Bulletin, No. 181, Dec., 1928.

the higher levels of illumination, by increasing the clearness of seeing, made the task easier and it follows that eye-strain and eye-fatigue would diminish. Here is evidence that better lighting may permanently benefit the visual organ. Measurements of visual acuity were also made at the beginning and at the close of the work-period and it was found that visual acuity was invariably better at the beginning of the period by about 1.3 per cent. If this difference in acuity be ascribed to the performance of work during the interval between measurements, it is interesting to note that the result of changing the level of illumination is several times greater than the effect of the day's work.

Much work must be done to establish the influence of lighting upon vision either temporarily or permanently; but owing to the great difficulty we have found in our attempts for many years to invade this field with methods which yield measurements, we may be excused for grasping at anything which points toward what we have good reasons for believing to be true. Quite aside from the good work which is being done by the U. S. Public Health Service, it is discouraging to us to find such low intensities of illumination being experimented with where the visual task is as serious as in post-offices. This is a good example of the lack of influence of present knowledge of lighting requirements for best seeing in its broadest sense.

The foregoing are only a few glimpses of a very complex science in the making. They have not been chosen, for their relative importance but rather as systematically arranged and fairly uniformly-spaced beacons in what was a great wilderness a decade ago. Even now it is a wilderness in which only a few clearings have been made, but we begin to see the magnitude and complexity of this new science of seeing. Its importance is not in doubt because human beings depend so much upon vision and because we have recently come indoors leaving nature's lighting behind and beginning over with relatively low intensities of illumination and with light-sources which can be used carelessly. But we have a great advantage in the controllability of artificial light. When we know how to use it at least there is no obstacle to its adequate and proper use—excepting indifference or ignorance on the part of the user.

In closing, we present with some hesitancy Fig. 17 in which we have attempted to include with definite knowledge what we believe is at least an approximation of the unknown with which we have

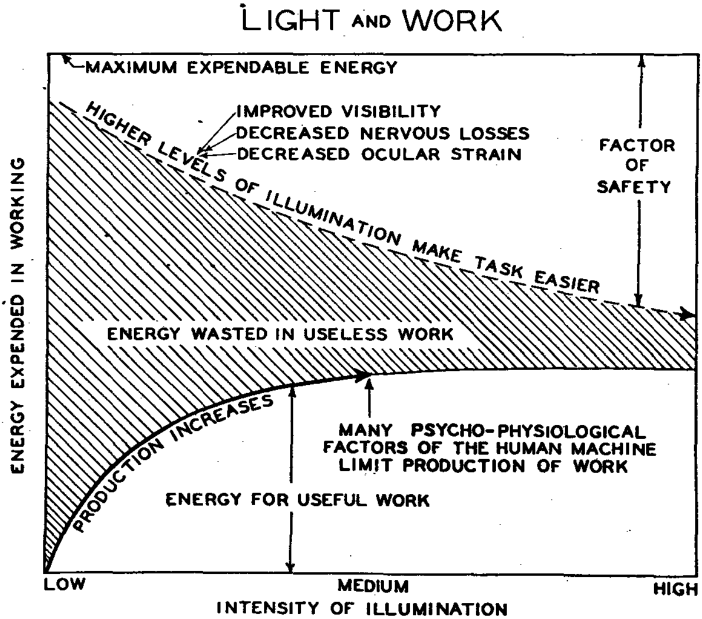


FIG. 17.

had a vague experience but pertaining to which we have practically no measurements. The foundation of any science is accurate measurements. We actually know little about anything until we have measured it. So it must be with the new science of seeing. We have already a vast accumulation of measurements but there are phases of it which have successfully defied measurement. The lower part of Fig. 17 is founded upon a great deal of knowledge. The upper part is no more than a diagrammatic view of what may be approximately true.

As the intensity of illumination increases the curve representing production through visual work flattens out. Beyond this point there is little or no increase in productive work with increase in foot-candles. However, if we consider the human being as a machine whose output is expended both in useful and in useless work we gain another idea of lighting for seeing. The human being in normal work does not expend the maximum amount of energy he is capable of. When he has no light he can expend this maximum energy without productivity if seeing is involved in the task. As the level of illumination is increased useful work increases and we believe useless work decreases. When the level of illumination reaches the point where increase in useful work is prevented by certain limitations of the human machine the useless work has also diminished considerably. However, we believe that there are further benefits from still higher levels of illumination; the task becomes easier and easier and useless work continues to diminish. This is a view which has been growing upon us for years and some of our researches are being directed toward ascertaining its justification.

Space has not permitted a discussion of many important factors which influence visibility such as direction, quality, diffusion, and distribution of light. Much of our work and many of our publications have dealt with such phases of lighting for best vision. However, the entire science of seeing is still so new and complex that it is difficult to coordinate all these systematically. Nevertheless, we hope that in the time and space available we have proved that a new science of seeing is in the making and that it can be the foundation of a new era and greater opportunity for lighting specialists in the work-world.

DISCUSSION

NORMAN MACBETH: I believe that this paper by Dr. Luckiesh and Mr. Moss is a very able presentation of the science of seeing. I hope you will study it and will use it in your everyday work.

My business for the last ten or fifteen years has had to do with the art of seeing. It may come under the science of seeing, but there is nothing new about it. First, I want to comment on some of the points made in this paper and amplify them, if possible.

On the first page it is stated, "During the present century great strides have been made in the production of artificial light and we now have highly controllable artificial light at a relatively low cost."

That is so. In my opinion, the cost is now so relatively low that it is hindering the advance in many channels. Light and lighting accessories are today almost in the same relative position as sugar in a grocery store; "if you want it, come and get it. There is no particular profit in going out to sell it to you."