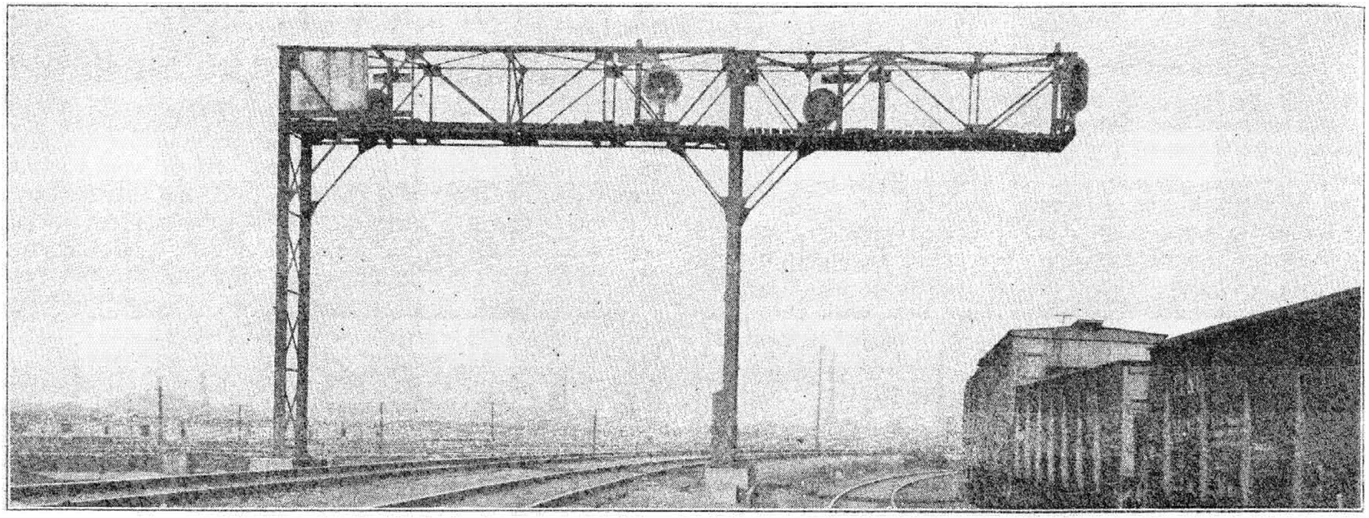

Color-Light Signals Should Be Designed to Convey Their Indications Without Confusion

Scientific Study of Light Signals

Some Fundamentals of Physics and Physiology as Applied to Modern Color-Light Signals Used in Railway Service

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PHYSICS and physiology are closely related in the art of signaling, for the function of all signals is the conveying of intelligence through physical means. Visual signals, convey intelligence through their physical elements by the physiological effect produced upon the human eye. In the design of a railway light signal, the two requirements of physics and physiology must be satisfied simultaneously. The designing engineer cannot neglect one at the expense of the other, if he wishes to produce a signal that will convey proper intelligence in a satisfactory manner. As it is through the eye that such intelligence must be conveyed to the brain, by the medium of light, it is essential that consideration be given to the physiological effect of light upon this organ.

From this consideration, it would seem that the logical procedure would be to work outward from the eye, constructing our apparatus in conformity with its characteristics so as to produce to the best advantage, the physiological effect desired. If this course is not followed and we ignore the physiological and consider only the physical, we may be lead to the construction of a device which, although perfect photometrically and optically, may fail when required to produce the desired physiological effect. Observation tests of such apparatus will show two observers reporting differently as to the effect produced. Even one observer will arrive at different and sometimes contradictory results, when observations are made at various times.

It is well, first, to examine the eye from the point of view of a physicist and then that of a physiologist. In so doing, we find the eye to be an optical instrument, possessing accuracy of construction and refinement of adjustments, far exceeding that which has been obtained in any optical device so far devised. We also find that it possesses some imperfections which could not be tolerated in precise optical instruments. Due to these imperfections, some physicists deem the eye an imperfect device when compared to some lens combinations that have been devised. But from a physiological view point, these imperfections of the eye become advantageous and make it the most perfect organ, we can conceive of for the purposes for which it is used.

A Study of the Eye

The optical equipment of the eye consists essentially of a compound lens, non-distorting and rectilinear, working at F 4 in conjunction with an automatic adjusting iris diaphragm. It can be considered as a camera, producing physiologically full size motion pictures in natural color. It is also a range finder and, to some extent, a photometer. The two most striking characteristics of the eye which have not yet been produced in a man-made optical device, are the automatic focal adjustment of the lens and the automatic diaphragm-changing aperture regulating the amount of light entering the eye. The latter affects, to a great extent, the visability of the light signal between day and night. This will be discussed later.

In the ordinary camera and other optical devices of like nature, the focal point of the lenses are fixed for objects a given distance from them. To focus objects at any other distance, it is necessary to change the position of the lens. The position of the lens in the eye is fixed, but when it is directed at an object, the shape of the lens is changed so as to bring the light rays from that object to a focus at the retina. This characteristic is termed "accommodation" by the physiologist.

From a physiological standpoint, the main factors for consideration in designing a light signal are: (1) The effect of the spectrum colors upon the retina, with respect to combinations of colors and with respect to the sensitiveness of the eye to colors of various intensities; (2) the persistence of vision for various colors at various intensities; (3) the minimum and maximum visual angles; and (4) the minimum and maximum intensities of illumination for good vision.

From a consideration of the effect of different colors upon the retina the proper colored lenses or roundels to be employed can be determined. A consideration of the maximum and minimum visual angles will determine the proper diameter of the lenses. From a consideration of the maximum and minimum illuminating intensities the amount of energy required to produce the necessary light flux can be determined.

Color of Lenses

In railway signaling, four colors—red, green, yellow and white—are in general use. Signal departments of various railroads having adopted as standard, some combination of these colors.

Red has always been employed to signify danger. The natural physiological effect of red upon the mind is to produce a sense of danger. It is also a natural physiological effect to associate white with clear or safety.

For indicating a condition between absolute danger and absolute safety, green has long been used and for a three indication signal, red, green and white were adopted. For certain physical as well as physiological reasons, white has proven to possess undesirable characteristics as a safety indication. In later practice, green has been substituted as signifying safety and yellow, caution. This combination of red, yellow and green is more commonly used at the present time than red, green and white.

The various colors affect the eyes in varying degrees of sensitivity. Sensitivity to different colored lights seems to depend upon the wave length and frequency, beginning with red, gradually increasing to a maximum between yellow and green, and decreasing toward the blue and violet. From this it is evident that yellow and green are the colors most sensitive to the eyes, the degree of sensitivity depending on the intensity of the color. For low intensity, the eye is more sensitive to the action of the green rays than to those of yellow or red. For high intensities, the yellow predominates. Sensitivity, as referred to here, pertains to visability and not to that sensation caused by lights of high intrinsic brilliancy, which causes dazzling and discomfort to the eye. The sensation causing discomfort is known as glare and is often popularly confused with sensitivity. The causes producing the sensation due to glare must be guarded against in the light sources used for railway light signals.

What Causes Glare?

A predomination of glare may magnify the faults due to a tendency of color blindness in eyes that have to be constantly trained upon such lights as is necessary in high speed train operations. It is difficult to give a clear definition of glare, therefore we will consider only the most prominent cause, which is the entering into the eye of radiations, other than those which produce light to which the eye is sensitive.

For pure green and yellow light, for which the eye has the highest sensitivity, all the radiations produce visability. The radiation or waves which produce sensation of light are of the same nature as heat. Therefore the radiations entering the eye which do not produce visibility produce heat. The absorption of heat for a given light sensation, is much greater for red and violet light than for yellow and green lights. The effects of overheating is manifested immediately from lights of long wave lengths, but the eye recovers quickly. The effect of the short wave lengths is not felt for some time, but recovery is very slow.

Less harm is done by red radiation than violet, this is due to the long wave length of the red and the short wave of the violet; therefore lights containing violet and ultra-violet rays are objectionable, for signal use. White light contains a larger percentage of violet and ultra-violet rays than any other light, and where such lights have been in use, it has been found necessary to make provisions for subduing them. Two methods have been employed, one by placing a wire screen in the path of a light beam, the other and more effective means is to filter out the violet rays. Ordinary window glass acts as a filter for part of the violet rays. A glass giving complete protection was invented some time ago by Drs. Schang and Stockhausen. To this glass, they gave the name of Euphor. This glass filters out completely the ultra-violet rays and does not absorb more than two to three per cent of the visible light rays.

The colors, as derived prismatically from sun light, have a high percentage of visibility whereas in those derived from artificial lights, the percentage of visible radiation is small compared to the power radiation which enters the eye. In the prismatically derived colors, the only radiation or wave lengths entering the eye, are those that produce the color sensations, excepting at each end of the spectrum, that is, in the ultra-red and violet rays. In the light signal, the colors are not derived prismatically but by a process of filtering or absorbing light rays from a radiant source. The colored roundels or lenses placed before a lamp do not produce color, these glasses act simply as filters preventing all colors except the one desired from passing through. Thus a red roundel does not produce red light, but by preventing the passage of all other colored rays, the red rays from the light source are made visible to the eye. If the source contains no red rays, the result will be black denoting the absence of color.

It is essential therefore, that the light source be capable of producing the necessary colors. The most efficient lens combinations or the highest quality of colored glass cannot compensate for a deficiency of color in the light source. Here, the light signal designer must appeal to the lamp manufacturers who are, we find, concerned in producing a lamp that will give a pure white light similar to sunlight. This result, the manufacturers have accomplished to a very high degree, but not by means of a lamp that has the same spectrum as sunlight, but by one that produces a white light sensation to the eye by the combination of two or more complementary colors. Here too the lamp designer must, like the signal designer, give consideration to the physiological. This, he does by combining red, yellow and green light in the proper proportions to fool the eye into believing it is seeing white light. Unfortunately when producing this effect, there is also produced a large number of heat and invisible rays that produce glare and other discomforts to the eye. This is especially true when the light enters the eye directly from the lamps as is the case when observing a light signal.

In electric lamps now used for signals, the percentage of red, yellow and green rays is not the same for each color. The percentage of visible radiation of the lamps is small compared to its total power radiation, which is in the form of heat and invisible rays. In the electric lamps, so far developed, the percentage of visible rays of any one color is not sufficient to produce enough candle-power to allow of projection for long range signaling. It is necessary that other rays be allowed to pass through the roundels in the proper proportions to give the necessary penetration and at the same time cause in the eye the physiological effect of the color desired. The red rays, which are low in visibility, can be made to appear much brighter if a small percentage of yellow rays, which are high in visibility, are allowed to enter the eye at the same time. The yellow causes a light sensation in the eye and if their percentage is not too high as compared to red, the eye will convey to the brain a sensation of red much brighter than if only red rays were used.

Reflected Light is Composed Largely of Visible Rays

If the light from a lamp falls upon a colored object, the eye will observe the objects by reflected rays; these rays will have only the color value of the objects illuminated. Very few rays other than the visible ones enter the eye by reflected light from colored objects, all other rays being absorbed by the object. It is this effect which we endeavor to produce in the light signal by taking into consideration the spectrum characteristics of the lamp employed and the composition of the colored lenses or roundels used. It is not only necessary that the composition of the colored glass used in the lenses or roundels be such that it will transmit the desired color only, but that it will also prevent the transmission of undesirable heat radiations and light waves which cause glare.

If a lamp could be produced giving only the colored rays required, this problem would be much simplified. Colored lenses could be dispensed with and a considerable amount of the energy, which in the present light source is wasted in producing invisible heat rays, could be used efficiently.

Another physiological problem for consideration is the possibility of producing false color sensations in the eyes. Signal men, as a rule, consider the term "false indication" to mean the effect produced by a head light beam or other foreign light reflected from the signal. What we refer to here, is the effect produced when the eye is suddenly directed from one color to another. It is due to the characteristic known as "persistence of vision". A light sensation in the eye does not cease at the same instant that the light producing it is extinguished, but persists for some appreciable time afterward. For example; when the eye is directed for some time on a red light, which is suddenly replaced by a green one, the sensation is not that of green, but a combination of green and red. This sensation will prevail as long as the sensation of red remains. Owing to this characteristic the colors that succeed each other in giving signal indications from danger to clear, should be selected so that the combination of the danger and caution colors will not momentarily produce the physiological effect of the color indicating safety. Referring to the combination of the spectrum colors, it has been found that 57 per cent of them can be produced by combination of two or more of the others. Red and green mixed in proper proportions will produce white. In a signal using red for danger and white for clear, the caution indication should be some other color than green. Yellow and red will not produce white, therefore yellow can follow red without the physiological danger of producing the white sensation in the eye.

The safest color to use for giving a clear indication is one that cannot be produced by a combination of any other two colors. Three of the spectrum colors have this property; they are red, violet and green. As violet rays give poor visibility, green is the best choice for giving the safety indication. Yellow ranking next to green in visibility and absence of glare makes it a desirable color for a caution indication.

The persistence of vision in a physical sense would seem at first thought to be an imperfection in the eye, but when we consider that without it the moving picture would not be possible, we see that it becomes an advantage from a physiological viewpoint.

Proper Size of Lens

To determine the proper size of lens, we should first note which characteristic of the eye enables us to detect the relative size of objects. We find that this is due to the angle at which light rays enter the eye from the extreme edges of the object viewed. This angle is known as the visual angle.

Figure 1 shows a diagrammatical representation of this angle. The rays from the object *A* at *C* distance from the eye will have an angle *F*. The same object at

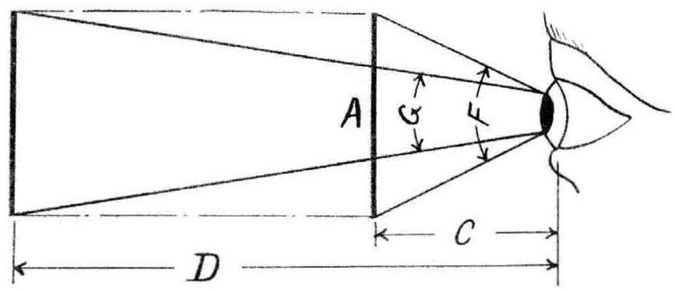

Fig. 1—Relative Size of An Object Depends on the Visual Angle

D distance will have a smaller angle *G* and will have a relatively smaller apparent diameter than when at *A*. From this, it will follow that as the object recedes from the eye, its apparent diameter will be decreased until the object disappears. This angle is known as the minimum visual angle which for a normal eye is an angle of 1 min. (1/60 deg.) At this angle, the eye can see an object only as a point, in order to see it clearly and with comfort the angle of the object must be at least five times this or 5 min. The diameter of a disc, which is comfortably visible is given by the formula:

$$A = \frac{2 D \pi}{21600} \times 5$$

in which *A*=diameter in inches or feet and *D*=distance in inches or feet. At a distance of 4,000 ft., which is about the maximum range required of the light signal, a disc to be clearly seen by reflected light, must have approximately a diameter of 66 in. From such a disc, the light rays are entering the eye from all parts of its surface and all at different angles to each other. It is not practical to construct, for light signal use, a lens or reflector combination having a diameter of 66 in., but fortunately the physiological conditions are somewhat different when light enters the eye in a projected beam from lenses or parabolic reflectors. In such cases, to a certain extent, the rays are parallel to each other, and not at different angles as in the case of the disc.

This is illustrated in Fig. 2 which shows that the light rays emanating from the luminous lens *B* are parallel to each other, entering the eye in parallel lines instead of angles. The rays do not form a visual angle on entering the eye, therefore the physiological effect of the size is not present and the eye cannot determine the size of such a light source. Because of this, it can be seen that for long distances, the eye cannot determine the relative size of two parallel light sources. Even, if they are placed side by side, a 3-in. diameter lens will appear as large as a 10-in. diameter lens. Of course the field of vision will be in relative proportion to their size; that is, the eye will detect the light from the larger lens easier than from the smaller one. What then, would be the apparent size of a light source which will send only parallel rays into the eye? This can be explained by referring to the visual angle at which objects will come into focus at the least muscular strain in the eye. When the eye is directed at an object and not moved, the maximum angle at which the object is in sharp focus is about ½ deg., everything outside of this is indistinct. This is known as the maximum visual angle. We are therefore, able to estimate directly the size of objects by muscular sensation of strain in converging our eyes to bring the light rays from the object to a focus at the retina of the eye. The amount of this convergence depends upon the angle at which the light rays enter the eye. It also depends upon the distance we are from the object, the farther away the less divergence; and it is a physiological fact that for the normal eye, objects over 100 ft. away come into focus without any muscular sensation.

Due to this fact, the eye when unaided by intervening objects, can judge fairly accurately the size of objects not exceeding a distance of 50 or 60 ft., but for distances above 100 ft. it fails entirely. An interesting example of this is shown in our ordinary estimate of the apparent size of the sun and moon; each appears to be about a foot in diameter. When we look at the moon in mid-heaven, our eyes directly inform us that it is at least a 100 ft. away, on the other hand, due to the absence of intervening objects, we instinctively estimate the distance as the least possible, consistent with the non-convergence of our eyes, and accordingly imagine the size of the disc to be about that of a ball which at a distance of 100 ft. or so, would subtend the same angle of ½ deg., that is, about a foot.

When we look into a parallel beam of light, the lens of the eye assumes its flattest form which exerts the least muscular sensation in order to bring such rays to a focus on the retina. This sensation tells us that the object is over 100 ft. away and its apparent diameter will be the same as an object 100 ft. distant, which subtends the same angle as the maximum visual angle. This diameter will be approximately 12 in. or ½ deg.

Apparent Size of Any Parallel Light Source

Therefore a strong parellel beam, although its source may be several thousand feet distant, will cause the physiological effect of size to be one foot in diameter. This is true, even though the light in reality may be very small or very large. This is evident in Fig. 2, in which it is shown that considerable of the light rays do not enter the eye at all, but the amount which does enter is the same for a small or large lens, being the amount falling within the diameter of the pupil of the eye. It follows from this, that a light signal source would not necessarily have to be of large dimensions and that possibly a 3-in. lens would be sufficient to give a long range indication. This would all be true, if the light rays were absolutely parallel which can only be true with an infinitesmally small light source and as all light sources have physical dimensions, it is not possible to send out all the light rays parallel within a narrow beam from a small lens.

It is physically impossible to keep the eye within this beam when approaching a signal at close range. While at a range of 4,000 ft., the eye would see a light source as one foot in diameter, only while it is situated in the beam, but as it approaches the light, and on account of the physical relationship of the signal to the track, the eye is gradually drawn out of the parallel beam and is affected by the diverging and converging rays due to the inaccuracy of the lenses and the physical dimension of the light source. Under these conditions the eye commences to see the light source somewhat under the same condition as the discs referred to above. With the lamps available and the lenses so far developed, it is not physically possible to obtain a maximum angle of light from the lamp with a lens less than 4 in. in diameter. These lenses must be used with a second lens, in order to give a parallel beam. From this, it would appear that the minimum diameter of the lenses, due to physical con-

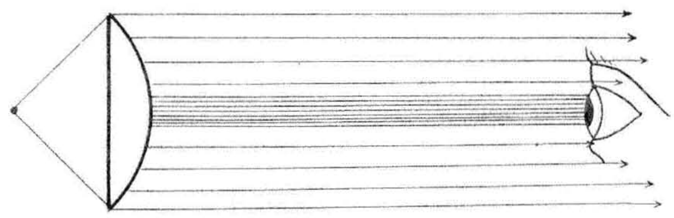

Fig.2—Parallel Rays Do Not Reveal the Size of the Light Source

ditions, could not be less than 5 in. As to the minimum size for physiological reasons, it follows that when the eye approaches within 500 ft. or less that, on account of diverging and converging rays and also the loss of the parallel beam, the lenses must be of such a diameter as to subtend an arc for comfortable vision.

Assuming that the conditions referred to take place at 500 ft. and using the formula referred to above, we find that the diameter of a disc clearly visible at that distance would be approximately 8½ in. in diameter. At this diameter the light source would appear as a point, if all the rays were convergent. By mounting the signal at the proper height and distance from the track, the eye can be kept within the direct ray of the beam within a distance much less than 500 ft., so that the effect of the parallel light will aid in giving the physiological effect of a 12-in. diameter lens within possibly 200 ft. of the signal, from which distance, the eye can readily compare the size of the illuminated lens with surrounding objects. It has been found in practice that a 8⅜-in. lens gives satisfactory illumination for signals that have to be mounted in such a position with reference to the track that the axis of their light beam will vary approximately 4 to 20 deg. from the line of vision between far and close up observations. A signal having an optical equipment embracing the same light flux as the 8⅜-in. combination, but using a 5-in. objective lens, will give equal results if it can be so mounted that its light beam axis will be within 4 deg. of the line of vision through the whole range of observation.

The advantage for the longer ranges is in favor of the smaller lens for the reason that the light flux per unit area is greater than for the larger lens, therefore the penetration would be greater. Where the ranges are the same, advantage can be taken of this fact by reducing the light energy for the smaller lens.

Primarily, the visability of the signal is due to the amount of light entering the observer's eye at any point within the signal's range. We must, therefore, determine the amount of light necessary to affect the eye for comfortable vision and then give consideration to the problem of projecting this amount to the extreme range of the signal. For the average eye to read comfortably ordinary print on white paper, it has been found necessary to illuminate the paper with a candle power of one foot-candle. The visability of light varies directly as the intensity and inversely as the square of the distance from the source. Therefore, to see clearly, by reflected light, the 66-in. disc referred to previously at a range of 4,000 ft., the illuminating source would have to be of 16,000,000 candle-power. Such an illumination would be as impractical

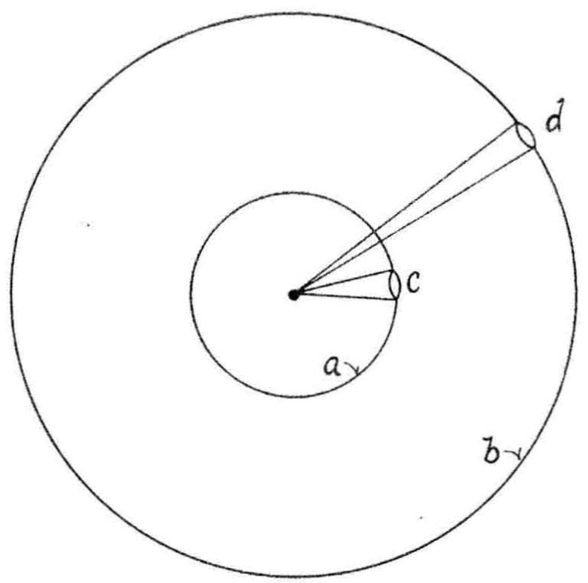

Fig. 3—Spherical Distribution of Light Flux

as a 66-in. lens, but the light signal does not give indications by reflected light, but by sending a direct ray into the observer's eye. In giving consideration to glare, we found that this characteristic has some physiological disadvantages, but when considering visability and range, we found it had some physical advantages in reducing the amount of light energy required to give a signal indication. The amount of light entering the eye is dependent on several factors, the most important of which are the intensity of the light source, the distance of the eye from the source and the area of the lens of the eye exposed to the light. In order to see more clearly the effects of these conditions it is necessary to review some fundamental considerations with respect to the distribution of light.

Inverse Square Law Not Applicable to Parallel Rays

From most primary light sources, the light flux is radiated in all directions. Keeping this fact in mind and referring to Fig. 3 let us assume an infinitesimal light source at the center of the circle *A* and *B*. The light source is of one candle-power. The radius of circle *A* is one foot and that of circle *B*, three feet. An observing eye placed at *C*, will be illuminated with one foot-candle but the one at *D*, in accordance with the inverse square law will receive an illumination of only 1/9 foot-candles.

Assume that *A* is the diameter of a sphere. As the light is radiated in all directions, it will uniformly illuminate the inner surface of such a sphere. If all the light on the spherical surface *A* were directed into the eye *C*, the increase of intensity would be in proportion to the ratio of the area of the sphere to that of the eye. The iris diaphragm of the eye is capable of closing and opening the pupil between 1.5 and 4 mm., from which we can assume for our illustration that *C* and *D* have a diameter of 1/16 in. the area of which is .00307 sq. in. The area of the sphere *A* is 1809.6 sq. in. Therefore the candle-power illumination of *C* will be:

$$\frac{1809.6}{.00307} \times 1 = 589,446.$$

The area of the sphere *B* is 16,286 sq. in., therefore the candle-power illumination of *D* will be:

$$\frac{16,286}{.00307} \times .11 = 583,540.$$

In comparing these results, we find that the inverse square law does not hold true, for if it did, the results for *D* would be 65,444 candle power. This illustration serves to show that when light is projected in a parallel beam from lenses or reflectors, it does not wholly comply with the inverse square law. This fact enables us, by the proper use of lenses or reflectors, to project a powerful beam of light having many thousand candle-power from a small light source.

To cause a light sensation, the light source can be of lower candle-power where the light ray is sent directly into the eye, than where the ray is reflected. The minimum luminosity of lights just visible is 0.00032 foot-candles for white, 0.0011, for green and yellow, and 0.032, for red. From these figures, we can assume that 0.032 candle-power must be projected to the maximum range of the signal in order that the eye can observe it.

The intensity of a projected light beam depends upon the angle of light embraced by the lens or reflector and by its diameter. Of all projecting means so far devised, the parabolic reflector can embrace the largest angle of light. But as reflectors have the physical possibility of causing phantom indications by foreign light entering the reflector, we will give here, consideration to lenses only as they do not possess this characteristic.

With well designed lenses, it is possible to embrace 170 degr. of the total light flux. If this flux is projected into a beam 6 in. in diameter, the intensity of such a beam will be 2,000 times the candle power of the source. From which it follows that with a 5-candle-power lamp, it is possible to project a beam of 10,000 candle-power.

The difference in intensity of a light beam to the eye—between night and day—is due to the physiological fact that the iris diaphragm of the eye is subjected to a marked expansion and contraction due to the action of light upon it. In bright sunlight, the diaphragm is contracted to a diameter of 1.5 mm., and in darkness, it is expanded to 4 mm. The amount of light that can enter the eye is governed by the area of the diaphragm openings, which opening, the physiologist terms the pupil of the eye. It follows that in observation of the light signal at night, the eye will receive over 7 times the illumination than at midday. Daylight observation of the signal can be favored by shading as much as possible the engineman's eye from direct daylight. In practice, the ordinary engine cab favors this condition. The main disadvantage due to the increased illumination at night is that of glare. But in a well designed signal in which consideration has been given to producing the proper color filters, this objection can be practically eliminated.