Visual Detection at Low Luminance through Optical Filters

H. RICHARD BLACKWELL, Vision Research Laboratory,
University of Michigan

● IN recent years, three optical filters have come into rather widespread use for night driving. Two of the filters are offered to the public in the form of "night-driving glasses." The third filter is offered to the public in the form of heat-absorbing windshields. The present paper is primarily concerned with the effect of these optical filters upon visual detection under conditions such as those encountered in night driving. Other implications of the use of optical filters for night driving are discussed to place the detection data in proper perspective.

Tne first section of the paper contains a qualitative analysis of the expected effects of optical filters upon visual performance in night driving. The second section describes a method for quantitative prediction of the effects of optical filters upon visual detection at low luminance. The third section contains a report of experiments in which the effect of the three optical filters upon visual detection at low luminance was investigated. The results of these tests were compared with the predictions made by the method described in the second section. The fourth section discusses implications of the experimental tests and the analyses for highway safety.

I. *Qualitative Analysis of Expected Effects of Optical Filter Upon Visual Performance in Night Driving*

During the past century, innumerable studies have been made of the relation between visual performance and the quantity of general luminance in the visual field. Large numbers of studies have involved visual detection (sometimes called intensity discrimination or contrast sensitivity). Other large numbers of studies have involved visual acuity. For a summary of some of these studies see Moon and Spencer (1). Lesser numbers of studies have involved other visual capabilities such as flicker and depth discrimination. In most of these studies, the luminance has been uniform over a large portion of the visual field. Studies of all visual capabilities made under conditions of uniform general luminance agree in showing that, at low luminance, a reduction in luminance reduces visual performance appreciably. At high general luminance, a reduction in luminance reduces visual performance either not at all or very little, or it may improve visual performance slightly. The precise amount of change in performance for a given change in general luminance has been shown to depend upon: (1) the general luminance level and (2) the visual capability studied.

Only a little research or clinical attention has been devoted to the relations of visual comfort and general-luminance level. It is generally believed that high levels of general luminance cause visual discomfort, even when the luminance is uniform over a considerable portion of the visual field. It is generally believed that uniform fields of low general luminance do not cause visual discomfort.

There have been a considerable number of studies of visual performance for fields of nonuniform luminance. Most of these studies have involved visual detection or visual acuity. For a summary of these studies, see Moon and Spencer (2). These studies agree in showing that luminance nonuniformity often reduces visual performance. Such losses in visual performance as a function of luminance nonuniformity occur at all levels of general luminance. Unfortunately, systematic studies have not been made to determine the relation between visual performance and level of nonuniform luminance, with a fixed degree of nonuniformity maintained at all luminance levels. As we shall see, such data are directly relevant to the problem of the use of optical filters in night driving.

There have also been a few studies, and much clinical observation, of the visual discomfort produced by nonuniformity of general luminance. Discomfort may be produced at any level of general luminance. Apparently, the higher the general luminance level, the smaller is the percentage luminance nonuniformity required to produce discomfort.

This relation explains the fact that the visual discomfort experienced by most people out of doors in the daytime can be reduced by a reduction in the high level of general luminance. Sunglasses are used for precisely this purpose. It is generally believed that the reduction in general luminance produced by the sunglasses causes little or no decrease in visual performance. This belief is based to only a small extent upon data relating visual performance to the general level of nonuniform luminance. It is based primarily upon the studies relating visual performance to the level of uniform luminance referred to above, which demonstrated little loss in performance when high levels of general luminance are reduced. Extrapolation of this relation to the case of nonuniform luminance is generally accepted. Our knowledge of the photochemical and neural aspects of vision provide bases for understanding why visual performance is relatively independent of general luminance level at high luminance. This independence must occur to a large extent whether or not the field of high luminance is uniform. Such experimental data as there are relating performance and the general level of nonuniform luminance confirm the validity of this extrapolation.

It is easily demonstrated that the visual discomfort produced by luminance nonuniformity at low luminance can also be reduced by reduction in all luminances reaching the eye. For example, the visual discomfort resulting from viewing bright lights at night can be reduced by wearing sunglasses. What will be the effect of general luminance reduction upon visual performance at low levels of nonuniform luminance? There does not appear to be any satisfactory experimental evidence on this point. It would seem reasonable to extrapolate as before and argue that general luminance reduction will have appreciable effects upon visual performance at low levels of nonuniform luminance. The photochemical and neural aspects of vision which produce large changes in visual performance as the level of general luminance is varied at low luminance may be expected to be present whether the luminance is uniform or nonuniform. Such a line of reasoning would suggest that sunglasses not be used to increase visual comfort at low luminance because of appreciable losses to be expected in visual performance. Thus, it is presumably acceptable to wear sunglasses in the daytime to increase visual comfort but not acceptable to do so at night.

These conclusions have apparently been widely accepted for many years. Sunglasses are widely used in daytime visual tasks but have not been often recommended for use in night visual tasks.

Recently, however, several commercial products involving optical filters have been recommended for use in night driving. The most widely advertised filters intended for use at night have been manufactured in the form of so-called night-driving glasses. One of these products involves pale-yellow light filters; the other involves amber light filters. These glasses have been advertised as safety aids for night driving. It has been claimed that the glasses increase visual comfort at night. There is little doubt that optical filters will reduce the visual discomfort caused by viewing bright headlights at night. In addition, however, it has been claimed either that the filters will not reduce visual performance at night or that the filters will actually increase visual performance at night. As noted above, there is reason to believe optical filters will always reduce visual performance at night.

The use of heat-absorbing glass in automobile windshields has become increasingly prevalent in recent years. This glass is primarily intended to reduce solar heating of the automobile interior. In addition to absorbing heat, the glass absorbs visible radiation. It is claimed that the heat-absorbing windshields increase visual comfort in the daytime. As optical filters, they undoubtedly do so just as do sunglasses. By increasing the optical density of the windshields toward the top through use of an auxiliary plastic layer, the windshields are made to reduce luminance nonuniformity in the visual field. In this way, visual comfort is undoubtedly increased even more than would be the case with uniformly dense optical filters, which merely reduce all luminance. The heat-absorbing windshields are clearly acceptable for day-

time use, since there is no evidence that filters will reduce visual performance in the daytime. It has also been claimed that heat-absorbing windshields reduce visual discomfort at night. They may be expected to do so, just as will all optical filters. There have also been claims that heat-absorbing windshields either will not reduce visual performance at night or will increase visual performance at night. There is reason to expect that the heat-absorbing windshields, like other optical filters, will reduce visual performance at night.

The claims made for the various optical filters utilize the term "glare". All filters are purported to reduce glare. It is stated in some advertising that glare produces highway accidents and it is implied that since the filters reduce glare, they will reduce highway accidents. It will be well to consider what is meant by the term. The Illuminating Engineering Society (3) differentiates between "disability glare" and "discomfort glare". Each type of glare is produced by nonuniformity of luminance in the visual field. Disability glare is defined as a condition of luminance nonuniformity great enough so that visual performance is reduced. Discomfort glare is defined as a condition of luminance nonuniformity not great enough to produce a measurable reduction in visual performance but one which, nonetheless, produces visual discomfort.

Most experienced drivers are aware that headlights produce disability glare under some conditions. It is common experience that object contrasts near headlights are washed out by a veiling haze, making objects difficult or impossible to see. Disability glare undoubtedly produces highway accidents.

Most drivers will affirm that headlights produce some degree of visual discomfort. Discomfort does not cause highway accidents directly. It can produce accidents indirectly, if discomfort produces a loss in visual performance or a loss in any other aspect of driver performance.

We can now place the claims made by the filter manufacturers in proper perspective. We have stated that there is reason to believe that filters will reduce visual performance at low luminance whether the general luminance is uniform or nonuniform. This means that we do not believe optical filters can reduce disability glare. We agree that optical filters will reduce visual discomfort at low luminance, as well as at high luminance. This means that optical filters can indeed reduce discomfort glare. Unless visual discomfort has an indirect effect upon some aspect of visual performance, however, reduction of visual discomfort will not improve visual performance. Hence, it appears likely that the net effect of using optical filters at night will be a loss in visual performance.

Thus far, we have considered the optical filters only insofar as they reduce general luminance, i.e., we have treated them as neutral filters. The heat-absorbing windshields are substantially neutral over the area used by most drivers. As noted, some of these windshields have a graded density which increases toward the top. This graded density is quite green at the top. Since few drivers view the road through the top of the windshield, however, it will suffice for our purposes to consider the heat-absorbing windshields as essentially neutral filters. As noted, the night-driving glasses are markedly chromatic. We may now consider to what extent the color of these filters introduces additional considerations.

The literature abounds in studies of the relation between the color of light and visual acuity at high general luminance. It must be concluded that the evidence is conflicting as to whether acuity is greater or less with yellow or amber than with white light. It is apparent that one variable taken alone must result in somewhat greater acuity with yellow or amber than with white light. This variable is the chromatic aberration of the eye. Any chromatic filter will reduce chromatic aberration to some extent. Unless other variables are also involved, acuity should increase with any decrease in chromatic aberration. The conflicting experimental literature suggests that variables must be involved when yellow or amber light is compared with white in addition to chromatic aberration. One variable which could work against yellow or amber light is the number of retinal receptors stimulated. Yellow or amber light will not stimulate as many receptors as white light so that the retinal receptive mosaic is coarsened with yellow or amber light, compared with white light. This effect will not necessarily be reflected in the luminous transmission of a filter, since luminosity does not depend critically upon receptor mosaic.

The writer is not aware of evidence that

visual acuity at low luminance has been studied systematically with chromatic light. At low luminance, acuity is greatly reduced. Under these conditions, the role of chromatic aberration will be of little significance. Thus, we do not have as much reason to expect the yellow or amber filters to increase acuity at low luminance as at high. The possibility exists, however, that visual acuity may be improved by highly chromatic filters, even at low luminance.

Our discussion of the effect of chromatic filters upon visual acuity is only cursory. The discussion will suffice, however, since it is the writer's opinion that visual acuity is not a particularly critical visual capability for use in night driving. This point of view may be justified in the following way. The night driver must detect certain objects in order to avoid accidents. In particular, he must detect the presence of pedestrians, parked cars, and other obstacles along the roadway. He is not required to recognize or identify details of these roadside obstacles in order to avoid collision with them. If the driver detects them, he will control his vehicle to avoid collision. Of course, the night driver must read signs, but accidents are seldom caused by poor sign-reading. In addition, the night driver must estimate speed and distance, and many accidents result from faulty estimates of these variables. But these estimates are not based upon simple visual acuity. The most important visual capabilities for night driving are therefore believed to be: (1) visual detection, needed to avoid pedestrian and obstacle accidents and (2) visual estimations of speed and distance, needed to avoid collisions with other vehicles.

Studies have apparently not been made of the influence of chromatic filters upon visual detection at low luminance. However, since detection can be shown to depend but little upon image blurring (4), there is no reason to expect a reduction in chromatic aberration to improve detection to any appreciable extent.

Studies have apparently not been made of the influence of chromatic filters upon visual estimates of speed and distance at low luminance. There seems to be no clear reason to expect improvements in these judgments by use of chromatic filters, but evidence on this point is lacking.

It has been suggested in some of the advertising claims that the chromatic filters improve visual performance at night because they reduce the amount of light scattered from the headlights either by the atmosphere or by the fluids within the eyeball. A reduction in scattered light would be expected to increase either visual detection or visual acuity. However, it is difficult to see how this claim can be correct to any appreciable extent. It is true that clear air scatters light selectively, in accordance with Rayleigh's formula. However, clear air scatters very little light over distances such as are involved in night seeing on the highways. When the atmospheric scattering is large, the scattering is essentially achromatic, due to the large particles associated with large amounts of scattering (5). Similarly, the fluids in the eyeball may be expected to scatter selectively in accordance with Rayleigh's formula. As Fry (6) has shown, however, the majority of scattered light within the eyeball is due to large particles which scatter nonselectively.

It thus appears unlikely that the chromaticity of optical filters will introduce effects upon visual detection at low luminance apart from effects due to their luminous transmission. However, the possibility of specifically chromatic effects exists logically until experimental work has been done.

It is claimed in the advertising that the yellow and amber filters are particularly effective in reducing visual discomfort. The writer has compared visual comfort in the laboratory with yellow and amber filters paired with neutral filters of a matched luminous transmission. For these tests, a visual environment was set up to simulate automobile headlights seen at night. The writer confirms that visual discomfort is less with the yellow or amber filters than with matched neutral filters. The explanation for this difference in visual comfort is not apparent.

CONCLUSIONS

The foregoing analysis has indicated that the three optical filters being used in night driving may be expected to reduce visual discomfort due to viewing bright headlights at night but that losses in visual performance are to be expected. Since the reduction of discomfort is a desirable ob-

jective in itself, it is essential that quantitative estimates be obtained of the losses in visual performance which are to be expected. A method of obtaining quantitative estimates of the effect of optical filters upon one important aspect of visual performance, visual detection, will be described in the following section.

II. Quantitative Method for Assessing The Influence of Optical Filters upon Visual Detection at Low Luminance

A method has been developed which permits predictions of the influence of optical filters upon visual detection at low luminance. The method is based upon a series of 81,000 visual observations previously reported by the author (7). The method is presumed to be applicable to the evaluation of any optical filter.

The visual-detection data which provide the basis for the method were obtained under conditions which may be described briefly as follows: Observers were seated before an opening in a uniformly lighted cube. A target could be presented, representing a luminance increment to the uniform luminance on the wall of the cube farthest from the observers' eyes. The luminance increment and the target size and duration could be varied. The general luminance of the cube could also be varied. A general view of the cube is given in Figure 1. The observers, cube, and a circular target are apparent. (The windshield placed before the observers was utilized in the experiments to be described in Section III.) Studies were made of the relation between visual detection and general luminance for circular target objects varying in angular size, for each of various target exposure times. Separate studies

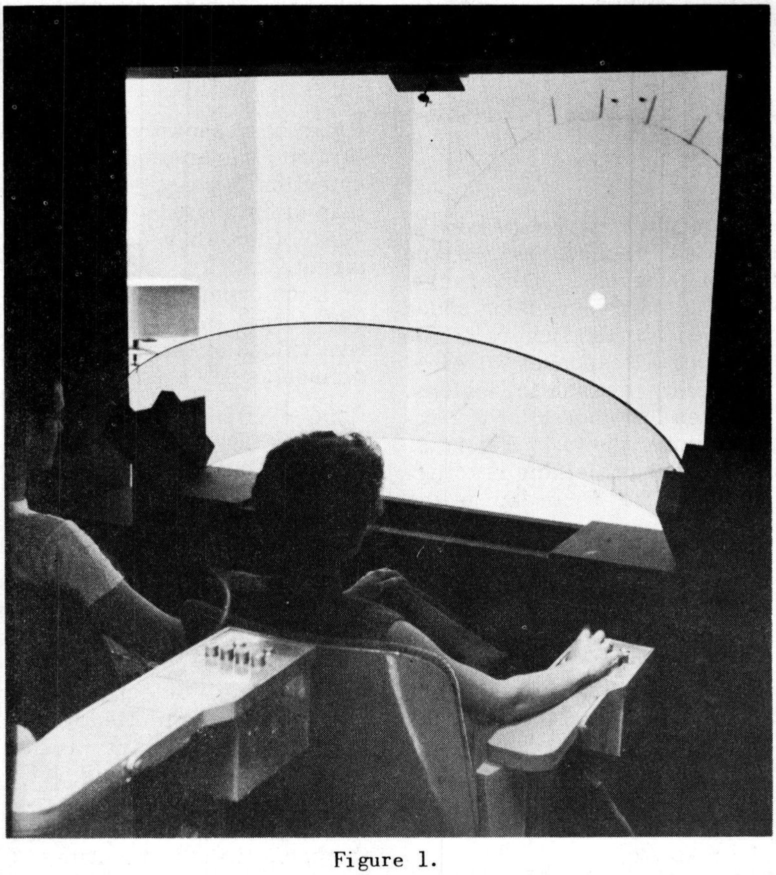

Figure 1.

were made with target durations of $1/1000$, $1/300$, $1/100$, $1/30$, $1/10$, $1/3$, and 1 second. At each target duration, target size was studied within the range from approximately 1 minute to 1 degree of arc. For each target size and each target duration, the influence of general luminance was studied from 100 to 1×10^{-3} foot-lamberts. In all, some 162 experimental sessions were conducted. The targets were presented by transillumination through a plastic screen which made up a portion of the cube wall. The target presentation apparatus is shown in Figure 2.

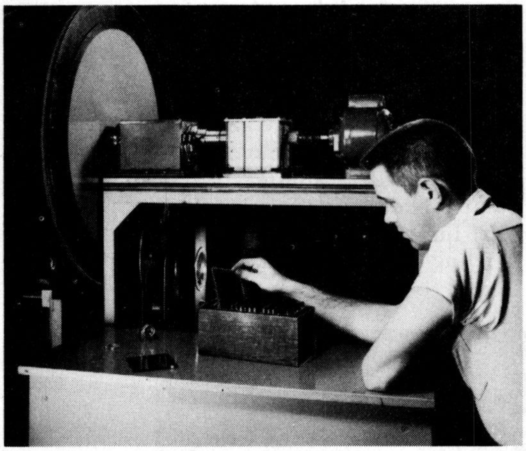

Figure 2.

The entire sequence of target presentations was automatically scheduled by a tape reading-and-timing device. Observers' responses were made by depressing coded buttons, shown beneath the fingers of one observer in Figure 1. Responses were recorded and scored by automatic devices. The apparatus used for control of the experimental sessions is shown in Figure 3. The operator is setting the tape reading-and-timing device. The recorder is the device to the left of the tape reader. The apparatus is described in detail in an earlier publication (8).

The accuracy of visual detection was specified by the probability of detection in a forced-choice situation. In the forced-choice situation, the target appears in one of four temporal intervals and the observer is required to indicate his detection of the target by correctly identifying the temporal interval in which it occurred. The influence of chance successes is eliminated by means of the relation:

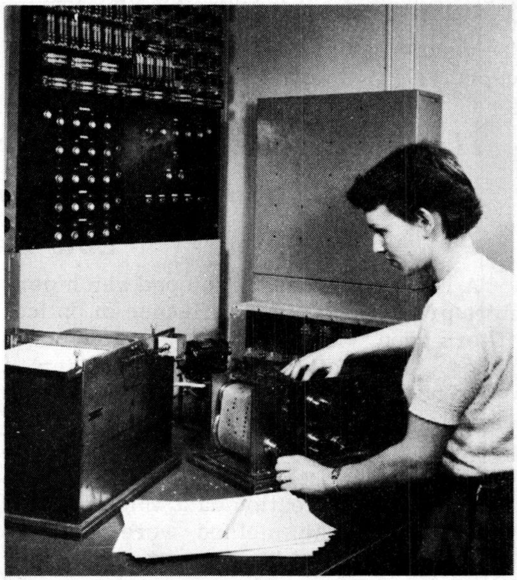

Figure 3.

$$p = \frac{p' - C}{1 - C} \qquad (1)$$

where p = corrected probability of detection,
p' = raw probability of detection,
C = the probability of chance success; in this case 0.25.

It has been shown in an earlier publication (9) that this method of measuring visual detection is more reliable and more valid than simply asking observers to respond "yes" when they detect the presence of a target.

Each experimental session consisted of 250 target presentations, 50 for each of five values of target contrast. Contrast is defined as

$$C = \frac{\Delta B}{B} \qquad (2)$$

where ΔB is the difference in luminance between target and background,
B is the general luminance.

The value of ΔB is taken as positive regardless of the direction of the difference. This procedure is justified by evidence reported elsewhere by the writer (10). The probability of detection, after correction for chance, was plotted against target contrast. A normal ogive was fitted to the data by the probit analysis (11). The target contrast eliciting any desired level of detection probability may be determined from the ogive fitted to the data. The justifica-

tion for fitting normal ogives to probabilities of visual detection is presented in an earlier paper (12).

In the data to be presented, target contrast values have been presented corresponding to 50-percent-detection probability. Following tradition, the term "threshold" will be used to refer to values of any physical parameter which correspond to 50-percent-detection probability. This low level of performance was selected for precision reasons: The contrast is most-accurately defined at this value of detection probability. Fortunately, the figures may be easily modified to correspond to any other detection probability of interest. It is shown in the earlier paper (7) that multiplication of the target contrasts by a suitable constant corrects the curves to any desired detection probability. For example, multiplying all target contrasts by two corrects the data to correspond to 99-percent-detection probability. Since logarithmic scales of contrast are employed, this type of correction may be made by sliding the log-contrast scale. The form of the relations shown in the various figures does not depend, therefore, upon the detection probability selected.

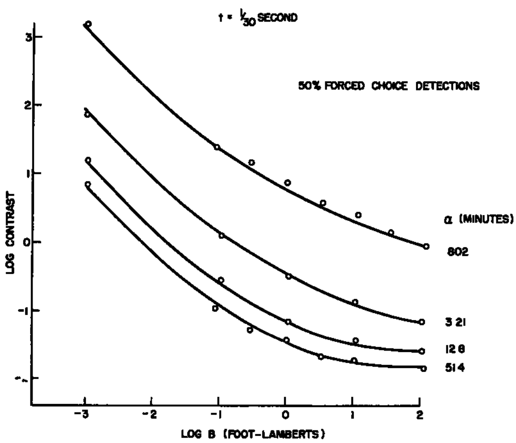

Figure 4.

Figure 4 presents the relation between log contrast and log background luminance for each of four target sizes. The angular subtense of the diameter of the circular targets is represented by the symbol α. These experiments were conducted with a target exposure duration of 1/30 second. This target exposure is considered appropriate for evaluating visual detection in night driving, where only restricted time is available due to the high velocity of the vehicle. Each experimental point is based upon at least 500 observations by two trained observers. The curves refer to a probability of detection of 50 percent. The data refer to "white" light of 2,850 K. for both target and general luminance.

Figure 5 presents interpolations from Figure 4, with log background luminance as the parameter.

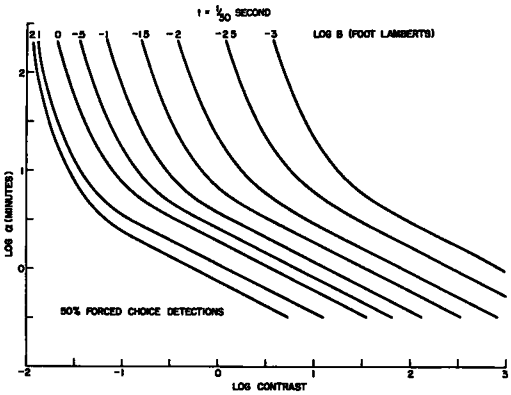

Figure 5.

Figure 6 presents crossinterpolations from Figures 4 and 5. Here we have the relation between log angular subtense (α) and log background luminance, with target contrast as parameter.

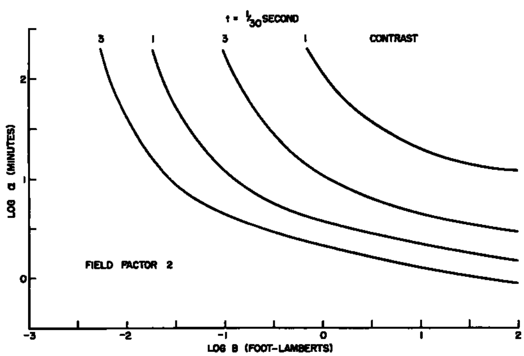

Figure 6.

In constructing these figures, relations between the experimental parameters obtained at target durations different from 1/30 second were employed to insure that the entire body of experimental data exhibited internal consistency. It will be well to note that the quantitative effects of optical filters on visual detection differ but little for data obtained with different target durations. Thus, whether the night

driver is considered to have $\frac{1}{30}$ second to detect a pedestrian or obstacle, $\frac{1}{10}$ second, $\frac{1}{3}$ second, or even 1 second will make little difference to the results of the analysis.

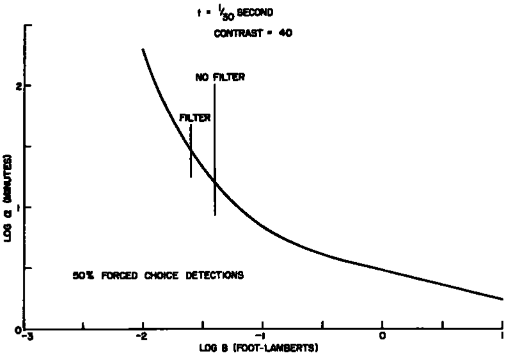

Figure 7.

Figure 7 has been constructed to exhibit the method of evaluating the effect of an optical filter upon visual detection, when the general luminance is uniform. The curve in Figure 7 is an iso-contrast contour, as are the curves exhibited in Figure 6. Now, for a given value of luminance, B, there is one value of threshold α for each iso-contrast contour. Thus, if we know target contrast, C, and luminance, B, we may read the value of threshold α from an iso-contrast contour. The vertical line in Figure 7 labeled "No Filter" cuts the iso-contrast contour at a given value of α, representing the threshold angular subtense of a target for a pair of values of B and C.

Any filter which absorbs light will reduce the value of B, the general luminance. If the filter is clear and unscratched, it will not affect target contrast. (If the filter is not clear and unscratched, the filter will reduce target contrast in addition. In our evaluation we will give the filters the benefit of the doubt and assume that they do not reduce target contrast.) Now, a filter absorbs a fixed percentage of the incident light, regardless of the amount of light. Thus, the effect of a given filter amounts to a fixed decrease in log B, regardless of the value of B. It is apparent from the curves in Figure 7 that such a decrease will always increase threshold α. To ascertain the amount of this increase, from the point on the iso-contrast contour where the vertical line marked "No Filter" cuts, proceed along the contour until you have moved the proper distance along the log B axis to correspond to the filter absorption. Read the value of threshold α corresponding to the reduced B and compare the value of α with that obtained with the original B. The increase in α is the proper measure of the influence of the optical filter upon visual detection.

Our experiments were all conducted at one viewing distance and α was varied by varying the physical size of the target. In the night-driving situation, the target size is fixed and α varies with the distance between the target and the driver. Thus, the practical implication of an increase in α is a decrease in what we shall call the "detection distance," that is, the distance between driver and target when detection first occurs.

One interesting aspect of the effect of optical filters upon visual detection with uniform general luminance is now apparent. The magnitude of the increase in α produced by a given filter is not a fixed quantity but depends upon the physical conditions encountered. From our example in Figure 7, it is apparent that the percentage magnitude of α increase is determined by the slope of the iso-contrast contour over the range of luminance values of interest. It is apparent from the contours in Figure 6 that the extent of α increase resulting from use of an optical filter depends upon the exact values of both B and C. In general, the extent of α increase for a given filter will be greater the smaller the value of B or the larger the value of C.

Let us next develop a means of evaluating the effect of an optical filter when the general luminance is nonuniform. To do so, we must employ information on the influence of nonuniformity upon visual detection. Here we must use data on what has been called "disability glare." These data have been summarized by Moon and Spencer (2).

For simplicity of exposition, we shall hereafter refer to luminance nonuniformities in the usual way as "glare sources." We have avoided use of this term to this point so as not to confuse disability and discomfort glare. In the analysis which follows in this section, however, it will be clear that we refer to disability-glare effects exclusively.

Moon and Spencer showed conclusively that the disabling effect of glare may be evaluated in terms of the concept of a veiling luminance. The physical interpretation of this concept is that light which enters

the eye from the glare source does not entirely come to focus on the retina in the image of the glare source. Some of the light is scattered onto other parts of the retina. The glare source thereby adds a veiling luminance, B_V, to both target and general background. The one physical quantity unaffected by B_V is ΔB, the luminance increment of the target.

Expressed in terms of contrast and general luminance, the effects of a glare source are that: (1) target contrast is reduced and (2) general effective luminance is increased. The quantitative relations are as follows:

$$C' = C \cdot \frac{B}{B + B_V} \qquad (3)$$

$$B' = B + B_V$$

where C' = contrast in the presence of glare, (4)
B' = effective luminance in the presence of glare,
B_V = veiling luminance produced by glare.

In order to evaluate the influence of optical filters upon visual detection in the presence of glare sources, we require a method for evaluating the value of B_V produced by a glare source. This may be accomplished by measuring the effect of the presence of glare sources upon the threshold value of α. The procedure may be described as follows: Let us determine the relation between B and α for a fixed value of ΔB, utilizing the data obtained without glare sources. We define ΔB by rewriting equation (2) as

$$\Delta B = B\,C \qquad (2a)$$

Now, to plot values of B and α for fixed Δ B, we select values of B, compute C for the fixed ΔB, and interpolate values of α corresponding to the values of B and C from Figures 4, 5, and 6. The result of such a process is an iso-ΔB contour such as is exhibited in Figure 8. Every point on the iso-ΔB contour defines a pair of values of B and C. In our example, we selected $\Delta B = 0.0161$, for reasons which will become apparent.

The general form of the contour in Figure 8 reflects the fact that glare sources serve to increase threshold α. Consider any one point on the contour. The value of B and the fixed value of ΔB defines a value of C. Now, the addition of a glare source

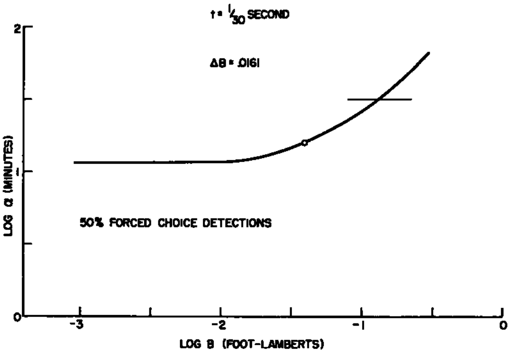

Figure 8.

increases B by the addition of B_V, and incidentally reduces C. However, since Δ B is unaffected by a glare source, we may represent the effects of a glare source by moving along the contour to the right an amount corresponding to B_V. As we move to the right along the contour, threshold α increases. The amount of increase in threshold α reflects the effect of the glare source upon visual detection.

Let us take a concrete example of the effect of a glare source. The open circle on the contour in Figure 8 defines the condition where $C = 0.40$, $B = 0.0402$. These values of C and B represent the point of intersection of the vertical line labeled "No Filter" and the iso-contrast contour in Figure 7. Threshold α for this condition is 11.5 minutes of arc.

Now suppose a glare source is added to the physical conditions of uniform luminance. It is impossible to measure B_V physically in the living eye. We may, however, infer its value from the increase in the value of threshold α produced by the glare source. In our example, suppose the value of threshold α in the presence of a glare source increased from 11.5 minutes to 31.6 minutes. Now, we lay off a horizontal line corresponding to log α, as shown in Figure 8. The intersection of the horizontal line and the iso-ΔB contour defines a value of B', the effective luminance in the presence of the glare source. In our example, $B' = 0.134$ foot-lamberts. Since $B = 0.0402$, $B_V = 0.094$ foot-lamberts. The value of $C' = 0.12$. In the presence of glare, then, B was increased from 0.0402 to 0.134 and C was reduced from 0.40 to 0.12.

The procedure illustrated permits us to specify the values of target contrast and effective general luminance in the presence

of glare. With these quantities at hand, we can evaluate the effect of optical filters upon visual detection in the presence of glare. To do so, we construct an iso-contrast contour for the value of C', in our example 0.12. In Figure 9, we have an iso-contrast contour for C' = 0.12, and also the iso-contrast contour for C = 0.40 already presented in Figure 7. The open circles represent the values of B and B' for the values of C and C' respectively. Thus, the arrow joining the two open circles signifies the effect of a glare source in increasing B and reducing C. The net result of these two effects is as shown an increase in the threshold α from 11.5 to 31.6 minutes.

We have already described the process for assessing the effect of an optical filter when no glare is present, in terms of Figure 7. Now that we have described the effect of glare in terms of values of B' and C', precisely the same procedure can be applied. Thus, in Figure 9, the effect of an optical filter in the absence of glare is shown by an increase in α defined along the 0.40-iso-contrast contour. The effect of the same filter in the presence of glare is shown by an increase in α defined along the 0.12-iso-contrast contour.

Figure 9 illustrates a most important point. Starting with the open circle on the 0.40-iso-contrast contour, we note that the use of a filter increases α in the absence of glare. Glare alone increases α as is shown by the open circle on the 0.12-iso-contrast contour. The use of a filter in the presence of glare increases α over and above the increase produced by glare. This Figure presents in a quantitative manner evidence to support the statement

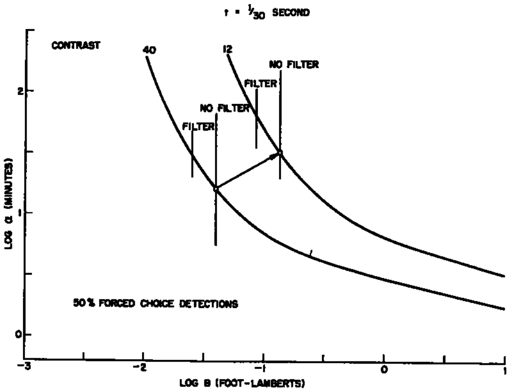

Figure 9.

made in Section I that optical filters would be expected to reduce visual performance in the presence of luminance nonuniformity in the same general way that they reduce performance with uniform luminance.

CONCLUSION

We have developed quantitative methods for evaluating the effects of optical filters upon visual detection in terms of the increase they produce in threshold α. A simple procedure has been described for situations involving uniform luminance. All that is required to assess a given filter is its luminous transmission and a statement of the physical conditions of general luminance (B) and target contrast (C). A more-complex procedure has been described for situations involving nonuniform luminance (glare sources). In this case we need in addition a measure of the increase in threshold α produced by presence of the glare source.

III. Experimental Tests of the Influence of Optical Filters Upon Visual Detection at Low Luminance

Experimental tests have been made of the effects of three optical filters upon visual detection at low luminance. These tests were undertaken primarily to investigate the validity of the quantitative method of predicting the effects of optical filters upon visual detection, described in Section II. The significance of such validation is obvious. If experimental tests show that the analysis is valid, the quantitative method can be used to evaluate filters other than those tested. Such an evaluation method would eliminate the necessity for experimental evaluation of each optical filter which can be produced by one or another manufacturer.

It is to be emphasized that the analysis of Section II ignored the chromaticity of the optical filters, assuming that chromaticity is not highly significant to visual detection at low luminance. If chromaticity were more significant than expected, the pre-

dicted effects of filters could err for this reason.

Furthermore, the analysis assumed that glare sources affect visual detection directly only, in a manner quantitatively defined by Equations 3 and 4. We noted in Section I the logical possibility that glare could influence visual detection indirectly. For example, glare could lead to discomfort and discomfort could influence visual detection. If an optical filter reduced discomfort, it could increase detection thereby. Although this indirect effect is logically possible, experimental tests of disability glare fail to exhibit it. However, if indirect effects were present, the analysis would presumably fail for this reason also.

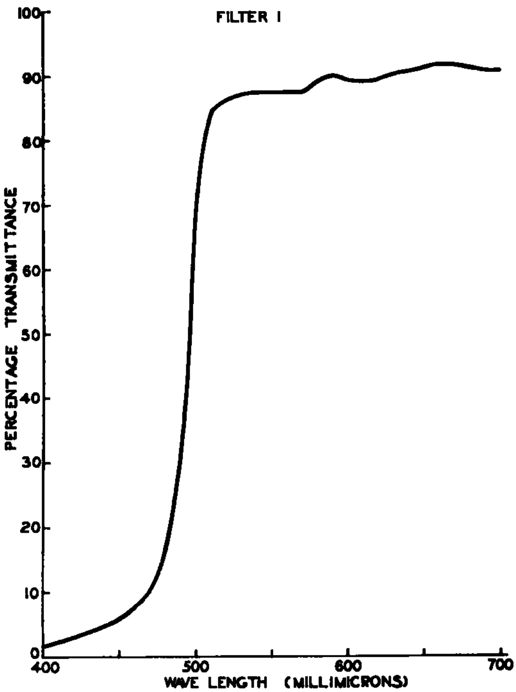

Figure 10.

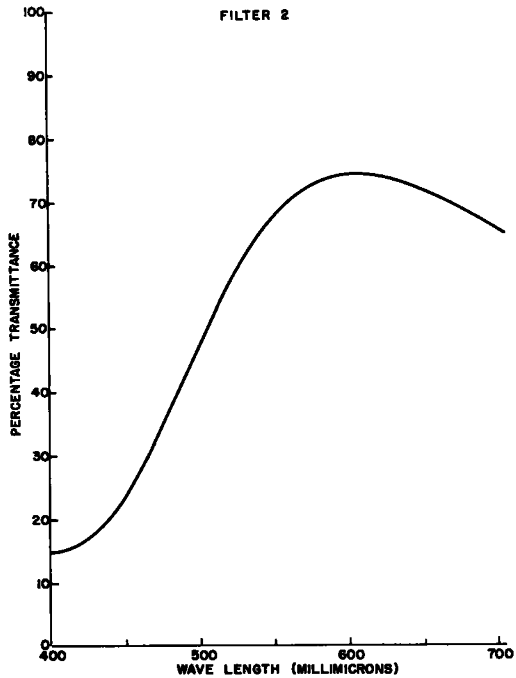

Figure 11.

Tests have been made on three filters. Two of the filters were made up in the form of night-driving glasses. These glasses were purchased from a local optician. The first of these (F1) is a pale yellow filter, the spectrophotometric curve for which appears in Figure 10. The luminous transmittance is 0.87 for 2,360 K. energy. The second (F2) is an amber filter, the spectrophotometric curve for which appears in Figure 11. The luminous transmittance is 0.69 for 2,360 K. energy. The third filter (F3) was made up in the form of a heat-absorbing windshield. The heat-absorbing windshield and a clear windshield (for comparison purposes) were loaned by the manufacturer. The spectrophotometric curve for the heat-absorbing windshield is presented in Figure 12. The luminous transmittance is 0.83, compared to a clear windshield, for 2,360 K. energy.

The basic experimental design involved comparing visual detection with and without the night-driving glasses and between the clear and the heat-absorbing windshield. Every reasonable precaution was taken to insure that the comparisons were without bias and of high precision, since the differences to be evaluated were expected to be small. The obtained results were compared with results predicted on the basis of the method described in Section II.

The basic experimental procedures were similar to those in the earlier published study (7), described briefly in Section II. Certain differences in procedure were adopted which will be described here.

In the present study the variable introduced within each experimental session was not target contrast but was target size. The use of target size as the intersession variable is not feasible under most ex-

perimental conditions, since probability of detection does not bear a simple relation to target size. At low luminance, however, the use of target size is reasonably satisfactory. The use of target size as the variable has the advantage that we can evaluate the predictions of α increase with a minimum of experimentation. Detection probability was evaluated as before, using a scale of target size rather than target contrast for the probit analysis, however.

In all cases, the two conditions to be compared were studied together before experiments were begun with other filters. A hundred presentations were made with a given target size, the first 50 with (or without) filters, the second 50 under the opposite condition. Subsequently, 100 more presentations were made with the same target size. The second time, the order of experimental conditions was reversed. Eventually, the procedure was followed for other target sizes. The order of filters versus no filters was random for different target sizes. Consequently, there is no reason to expect any bias due to the temporal order of the experimental conditions.

The observers were required to work for 100 target presentations at a sitting, occupying approximately 40 minutes. The same observers were required to return after a 5-minute rest for two more sessions of 100 presentations each. A third sitting followed a second 5-minute rest. The total time in each session exceeded 2 hours.

A total of 25, 500 experimental tests have been made, using six observers. These experiments were conducted in two series. The first series was completed in October 1952. This series consisted of tests of F1 and F2 only. The second series was completed in June 1953. This series consisted of tests of all three filters.

The following special conditions refer to the first series of experiments:

The target was a bright rectangle, whose height was six times its width. (This target was selected to represent the approximate dimensions of a pedestrian.) The target exposure time was 1/30 second. The color temperature of target and background luminance was 2,360 K. Experiments without glare were conducted with the target presented in the center of the large uniformly bright screen shown in Figure 1. In the experiments with glare, the large screen was covered with a black mask except for a central elliptical area intended to simulate the area of the highway illuminated by automobile headlights. The horizontal axis of the lighted ellipse subtended approximately 11 deg. at the eyes of the observers. The vertical axis subtended approximately 2. 5 deg. These

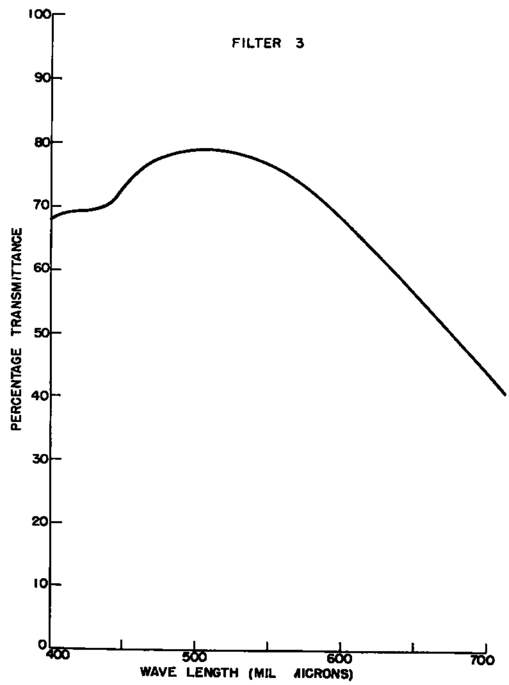

Figure 12.

dimensions were maintained in all tests. The target appeared half way to the right of the center of the elliptical lighted area in all cases. A pair of glare sources was mounted to the left of the target, as viewed by the observers. The separation between the glare sources and the distance from the glare sources to the target was scaled in terms of the target size used. Specifically, the following relations were maintained among the various elements of the visual task with respect to the height of the target, at all times:

Separation between "headlamps" = 0. 95. Distance from target center to center of headlamps = 2. 83. Thus, the visual display intended to simulate a target and opposing headlamps varied as it would normally vary with distance between the observer and the target. In the experiments with glare, the subjects were able

to look away from the glare sources for about 2 of every 12 seconds, the time between observer response and the warning signal for the next presentation.

The following special conditions refer to the second series of experiments:

The target was a bright circle. The target exposure was 1/30 second. The color temperature of target and background luminance was 2,360 K. Experiments without glare were conducted with the target presented in the center of the large uniformly bright screen referred to above. Experiments with glare were conducted under the same conditions except that one glare source was added at the left of the target at an angular separation of 6 deg. The clear and tinted windshields were mounted in front of the observers as shown in Figure 1. The windshields were intended for use in a 1950 Buick Super automobile. The windshields were carefully mounted with respect to the observer's eyes to maintain the relations which would have occurred in automotive use. Only two observers were used at one time, so that there were no observers positioned to correspond to seats in the rear of an automobile. As in the earlier experiments, the observers were able to look away from the glare source for about 2 of every 12 seconds.

TABLE 1

EXPERIMENT 1

Night-Driving Glasses, F1 (No Glare)

B = .097 C = .27
N = 5800 PR = 1.13

Observers' Initials	R	P
AM	1.00	0.50
LP	1.13	<0.001
HF	1.12	0.008
VL	1.12	0.002
NS	1.13	0.001
AK	1.06	0.12
Average	1.09	

TABLE 2

EXPERIMENT 2

Night-Driving Glasses, F2 (No Glare)

B = .099 C = .34
N = 3900 PR = 1.37

Observers' Initials	R	P
AM	1.30	<0.001
LP	1.48	<0.001
HF	1.37	<0.001
VL	1.45	<0.001
Average	1.40	

TABLE 3

EXPERIMENT 3

Night-Driving Glasses, F1 (Glare)

B = .525 C = 10
N = 6,000 PR = 1.10

Observers' Initials	R	P
AM	1.11	0.002
LP	1.03	0.21
HF	1.08	0.006
VL	1.01	0.43
NS	1.10	0.007
AK	1.04	0.10
Average	1.06	

RESULTS

October 1952 Experiments

The experiments conducted in October 1952 involved more experimental data than the later tests. As a consequence, more complete analysis has been made of these data. The observations made by each observer, with and without optical filters, were separately analyzed by the probit analysis. The data are reported in terms of a ratio of α increase, defined as the ratio of the threshold α with glasses to the threshold α without glasses. The ratio of α increase predicted by the method described in Section II is given for

TABLE 4

EXPERIMENT 4

Night-Driving Glasses, F2 (Glare)

B = 0.525 C = 0.10
N = 2,600 PR = 1.31

Observers' Initials	R	P
AM	1.31	<0.001
LP	1.24	<0.001
HF	1.23	<0.001
VL	1.23	<0.001
Average	1.25	

TABLE 5

EXPERIMENT 5

Night-Driving Glasses, F1 (No Glare)

B = .047	C = .41
N = 1,200	PR = 1.16
R = 1.09	P = .25

comparison. The significance of each α increase has been established statistically. The probit analysis of each set of data provides us with a threshold and a standard error of this quantity. Significance of the α increase caused by the optical filter

TABLE 6

EXPERIMENT 6

Night-Driving Glasses, F2 (No Glare)

B = 0.047	C = 0.41
N = 1,200	PR = 1.54
R = 1.51	P < 0.001

is in each case evaluated by computing a critical ratio from the probit values of threshold α. The quantity P defines the probability of obtaining so large a difference as that obtained by chance alone.

June 1953 Experiments

The experiments conducted in June 1953 were undertaken primarily to test the heat-absorbing windshield. Tests of the night-driving glasses were conducted to attempt to confirm the results of the 1952 experiments. Four of the original observers were used in the 1953 experiments, whose initials were: AM, LP, NS, and AK. The number of observations made by each observer was insufficient to justify a separate probit analysis. Consequently, the results of all observers were combined and probit analysis was performed on the combined data. Combined data may yield probit standard errors of excessive size, so that significance tests are probably underestimated.

The data for the eight experiments conducted in all are reported in Tables 1 through 8. In the tables reporting the results of these experiments, the symbols will have the following meanings:

B = general luminance (foot-lamberts)
C = target contrast
N = total number of observations
R = ratio of α increase
PR = predicted ratio of α increase
P = probability of chance occurrence of difference this large or larger

We may well begin by evaluating the overall effects of the optical filters investigated. It is to be remembered that values of R, the ratio of α increase in excess of unity represents losses in visual performance. (Implications of these losses for highway safety will be discussed in Section IV.)

First, the average value of the ratio obtained in each of the eight experiments exceeds unity. For F1, the values are 1.09, 1.06, and 1.09. It is to be recalled that this filter has a very high transmission (0.87) and that quite-small ratios were expected. Values for F2 are 1.40, 1.25, and 1.51. Values for F3 are 1.20 and 1.66. All individual values of the ratio exceed unity except one. Observer AM in Experiment 1 with F1 gave an experimental ratio of exactly 1.00.

There is no question but that the average ratios in each experiment except Number 5 represent statistically significant differences. (To estimate significance of the average ratios in the 1952 experiments, we combine the individual measures of significance by the familiar χ^2 pooling techniques. In each of the 1952 experi-

TABLE 7

EXPERIMENT 7

Heat-Absorbing Windshield, F3 (No Glare)

B = 0.040	C = 0.41
N = 2,400	PR = 1.25
R = 1.20	P < 0.001

ments we reach better than the 0.001 confidence level.) Since the significance test in Experiment 5 is probably underestimated, the difference obtained may be truly significant. At least, we are justified in concluding that F2 and F3 required significantly increased α under all conditions tested, and F1 required significantly

TABLE 8

EXPERIMENT 8

Heat-Absorbing Windshield, F3 (Glare)

B = 0.040	C = 0.41
N = 2,400	PR = 1.32
R = 1.66	P = 0.002

increased α under at least two of three conditions tested.

The results of all experiments may be summarized to better compare the predicted and experimentally obtained ratios of α increase.

Experiment	Predicted Ratio	Obtained Ratio
1	1.13	1.09
2	1.37	1.40
3	1.10	1.06
4	1.31	1.25
5	1.16	1.09
6	1.54	1.51
7	1.25	1.20
8	1.32	1.66
Average	1.27	1.28

The agreement between the average predicted and obtained ratios is striking. If we separate all data involving glare from those not involving glare, the following results are obtained:

Condition	Predicted Ratio	Obtained Ratio
Glare	1.24	1.32
No glare	1.30	1.27

These results indicate that, if anything, the obtained α increases are greater than predicted with glare and less than predicted without glare. Since a large value of the ratio of α increase represents a greater loss in visual detection, these data suggest that the filters are, if anything, more deleterious when glare is present than expected. The direction of this difference is opposite to that to be expected if indirect effects of glare were present.

It must be pointed out that there are several suggestive trends in the data. First, in all three tests of F1, less α increase was obtained than predicted. In tests of F2, two of three increases in α are less than predicted. In tests of F3, one of two increases in α is less than predicted. There is, therefore, a suggestion that the yellow and amber filters do not produce as great increases in α as predicted. However, this trend is no more suggestive in the tests with glare than those without glare, so it is probably unreasonable to attribute the trend to the reduction of discomfort glare.

It should be emphasized that all observers reported spontaneously that all filters increased visual comfort during tests with glare. There was no clearcut preference for one or another of the three filters tested. It should also be emphasized that our tests represented conditions of extreme glare. All observers found the tests as unpleasant as any night-driving situation they had ever encountered. They felt that the situation where they had to encounter the glare for about 10 of every 12 seconds represented good simulation of a condition of heavy traffic where glare sources followed one another in unpleasantly rapid succession.

CONCLUSIONS

The results of all experiments seem to validate the predictive method for evaluating optical filters to a satisfactory degree. The author will have little hesitation in using predictions made in this way in lieu of further experimentation of the type reported in this section. The implications of the quantitative analysis and of the experimental data for highway safety will be discussed in the following section.

IV. Night-Driving Implications of the Effects of Optical Filters upon Visual Detection

The quantitative analysis method described in Section II and the experimental tests reported in Section III are expressed in terms of laboratory concepts. It is our intention here to place our analyses and data in terms with more-practical relevance to conditions of night driving. All data discussed heretofore represent thresholds, defined by 50-percent-detection probability. We will now adjust these data to represent detection probabilities more useful for considerations of night-driving problems. Furthermore, the effects of optical filters are expressed in terms of increases in α. We will now re-express these effects in terms of practical highway parameters.

Let us first adjust the threshold data to

more-practical probability levels. As was indicated in Section II, we can adjust our data to different levels of detection probability by multiplying all values of threshold contrast by a constant. The constant 2 converts threshold data to 99-percent visual detection. In interpreting this figure, it must be recalled that in our experiments, observers know that targets were going to be presented, and targets were presented frequently. It has been shown (13) that multiplication of threshold contrast by an additional constant of 2 allows for the fact that night drivers do not know when to expect targets and that targets appear infrequently in night driving. We have adjusted the threshold data, accordingly, by multiplying all threshold contrasts by 4. When the data have been treated in this way, they are labeled "Field Factor 2". Iso-contrast contours are presented in Figure 13 representing Factor

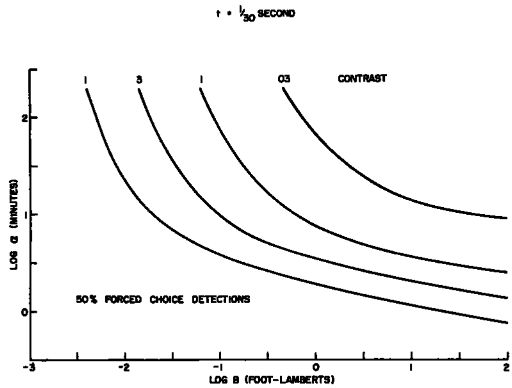

Figure 13.

2. (These are to be compared with iso-contrast contours presented in Figure 6).

Now, let us convert these new data into a useful highway parameter, detection distance. We convert values of α into distances for detection of the international highway test object, a square which is 16 inches on a side. The resulting replot of the data of Figure 13 appears in Figure 14.

We may use these data to compute the losses in detection distance produced by any optical filters. The method should be familiar in principle by now. If we know target contrasts (C) and general luminance (B), we can compute detection distance just as we computed α before. The effect of an optical filter in reducing B can now be assessed in terms of the reduction produced in detection distance. The vertical lines in Figure 14 demonstrate the method. It should be apparent that the quantitative loss in detection distance varies with the conditions of use of the optical filters. The

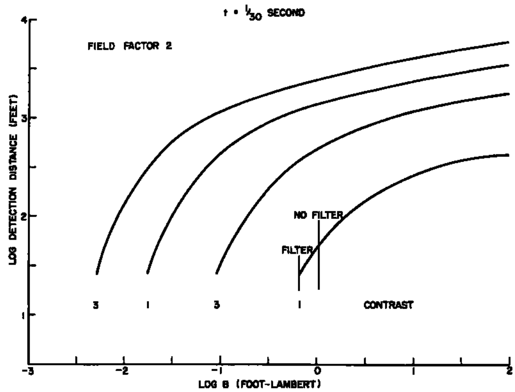

Figure 14.

percentage loss in detection distance corresponds directly, of course, to the reduction in log detection distance. The greatest percentage losses occur where the iso-contrast contours in Figure 14 are steepest. It is apparent from Figure 14 that the iso-contrast lines become steeper as log detection distance decreases.

This means that the percentage loss in detection distance produced by a given filter is greater the shorter the detection distance was without the filter.

When detection distance is already dangerously short, the percentage loss is great, whereas when detection distance is longer the percentage of loss is less. This is an unfortunate state of affairs, and one which was not foreseen until the detection data were examined with this problem in mind.

It will be worthwhile to indicate quantitative losses in detection distance to be expected with each of the three filters of interest here. Only by computing such losses for the same conditions of C and B can we obtain an adequate estimate of the comparative losses to be expected with the three filters. Our experimental tests did not involve the same values of B and C throughout; hence, comparisons among the filters on the basis of these tests can be misleading. In making these computations, the transmissions of the three filters have been evaluated at 3,050 K., the approximate

color temperature of automobile headlamps. The appropriate transmission values are: 0. 86 for F1; 0. 68 for F2; and 0. 84 for F3.

To give an idea of the range of losses in detection distance to be expected with each filter, two conditions were selected. The first condition was intended to represent the case where the largest losses would be found. For this purpose, we selected B = 1. 06 foot-lamberts and C = 0. 1. The detection distance without filters was approximately 50 feet. (This condition is represented by the vertical line labeled "No Filter" in Figure 14). For these conditions, F1 reduces detection distance to 79 percent of normal; F2 reduces detection distance to 55 percent of normal; and F3 reduces detection distance to 77 percent of normal.

The second example selected B = 1.06 foot-lamberts, and C = 0.3. Here the detection distance without filters was approximately 500 feet. For these conditions, F1 reduces detection distance to 90 percent of normal; F2 reduces it to 77 percent of normal, and F3 reduces it to 89 percent of normal.

It is to be emphasized that our method of utilizing the data of Figure 14 to compute detection distance losses corresponds to a physical situation in which headlamps are not used by the driver. Thus, the conditions chosen here for calculations represent twilight conditions when the driver has not yet turned on his headlamps.

When headlamps are used, the calculation of detection distance is somewhat more complex. As we have noted, the use of filters at low luminance increases threshold α . Thus, in order to see a given target, the driver must shorten the distance between himself and the target. When headlamps are not used, nothing changes as the driver approaches the target except α . However, when headlamps are used, B changes as the driver approaches the target, in accordance with the inverse-square law of headlamp illumination.

We may represent the entire situation when headlamps are used in the manner shown in Figure 15. The relation between B and detection distance for any viewing situation is represented by a line of slope -½. Thus, one such line represents the situation without a filter. A second such line, displaced with respect to B by the absorption of the filter, represents viewing with an optical filter. The lines displayed in Figure 15 represent an arbitrary assumption of the headlight candlepower and the reflection factor of the target. They will suffice, however, to illustrate the characteristics of the relations which must exist when headlamps are used.

To determine the detection distance without a filter, we select values of B and C where the no-filter line intersects an iso-contrast contour. To determine the loss in detection distance produced by a given filter, we determine the intersection of the filter line with the same iso-contrast contour. The optical filter used in the constructions of Figure 14 and 15 is the same. It is apparent from these figures, that detection distances losses are greatly reduced when the situation of interest involves the use of headlamps.

Calculated losses in visual detection distance have been computed for two conditions involving headlamps, intended to establish the range of losses to be expected. In the first instance, B = 0. 125 foot-lamberts; C = 0. 3. Detection distance without

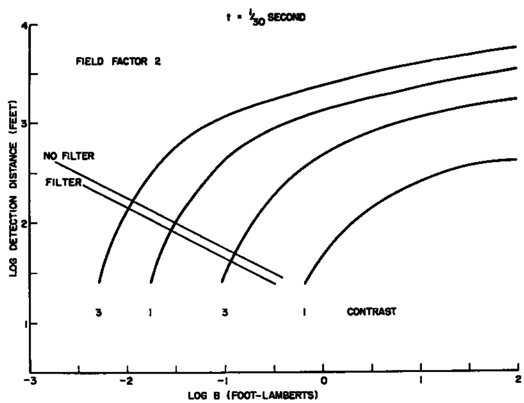

Figure 15.

filters is approximately 50 feet. Under these conditions, F1 reduces detection distance to 94 percent of normal; F2 reduces it to 85 percent of normal; and F3 reduces it to 92 percent of normal. In the second instance, B = 0. 125 foot-lamberts; C = 1. Detection distance without filters is approximately 500 feet. Under these conditions, F1 reduces detection distance to 96 percent of normal; F2 reduces it to 90 percent of normal; F3 reduces it to 95 percent of normal.

There is one further way in which the effect of optical filters can be expressed.

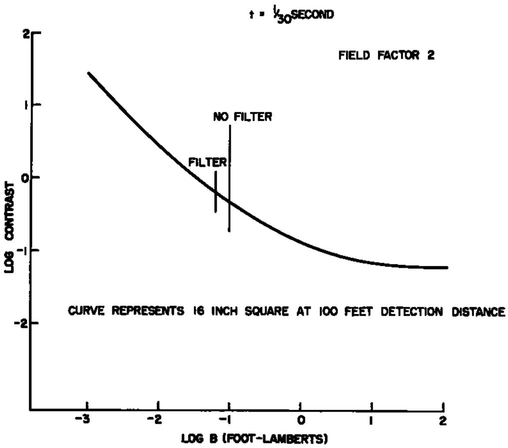

Figure 16.

It is reasonable to assume that there is a minimum detection distance below which detection will be useless in preventing accidents, due to the required stopping distance for the automobile. If we assume such a minimum detection distance, then the effect of optical filters will be to reduce the number of targets which will be detected. Data prepared to represent this case are presented in Figure 16. The curve in this case is an iso-α contour corresponding to the international highway test object viewed at a distance of 100 feet. The value of B is fixed by headlamp illumination at 100 feet and target reflectance. Thus, we may use the iso-α contour to specify how great target contrast must be in order for detection to occur. The intersection of the horizontal line marked no-filter line and the iso-α contour defines the target contrast required when no filter is used. The intersection of the other horizontal line and the iso-α contour defines the target contrast required with the filter. All targets of contrast greater than the contrast required will be detected; all other targets will presumably be struck.

We may specify the percentage increase in the minimum target contrast required when each of the filters is employed. As before, we have analyzed the effect of the filters under two conditions intended to establish the range of effects to be expected. In the first instance, B was taken as .01 foot-lamberts. The minimum target contrast requirement is increased by 16 percent with F1, by 47 percent with F2, and by 19 percent with F3. In the second instance, B was taken as 1 foot-lambert. In this case, the minimum target contrast requirement is increased by 7 percent with F1, 19 percent with F2, and 8 percent with F3. These results are independent of whether or not headlamps are used.

CONCLUSIONS

Threshold data presented in Section II have been converted into a form suitable for use in assessing the highway significance of losses in visual performance at low luminance due to optical filters. Using the percentage reduction in detection distance as a criterion, we find conditions in which detection distance is cut to as little as 79 percent of normal with F1, 55 percent of normal with F2, and 77 percent of normal with F3. Losses as great as this occur under twilight conditions in which headlamps are not used. Conditions can be found under which these percentage losses occur when the detection distance without filters is 100 feet or less. Losses of smaller percentage magnitude occur whenever the use of headlamps is involved.

Losses in visual detection may also be specified in terms of the number of targets not detected at a minimum detection distance. Percentage increases in the minimum required target contrast can be as great as 16 percent for F1, 47 percent for F2, and 19 percent for F3.

The losses in visual detection capability resulting from the use of optical filters at low luminance appear to be sufficiently great so that the use of such filters can scarcely be recommended unless drivers using such filters slow their vehicular speeds accordingly.

References

1. P. Moon and D.E. Spencer. "Visual data applied to lighting design." J. Opt. Soc. Amer., 34, 605-617 (1944).
2. P. Moon and D. E. Spencer. "The visual effect of non-uniform surrounds." J. Opt. Soc. Amer., 35, 233-248 (1945).
3. I. E. S. Lighting Handbook. Illum. Eng. Soc., New York (1947).
4. H. R. Blackwell. Unpublished research.

5. W. E. K. Middleton. Vision Through The Atmosphere. Univ. of Toronto Press, Toronto: 1952.

6. G. A. Fry. Paper delivered at the Light and Vision Conference, Univ. of Mich., June, 1953.

7. H. R. Blackwell. "Brightness discrimination data for the specification of quantity of illumination." Illum. Eng. N. Y., 47, 11, 602-609 (1952).

8. H. R. Blackwell, B. S. Pritchard, and J. G. Ohmart. "Automatic apparatus for stimulus presentation and recording in visual threshold experiments." J. Opt. Soc. Amer., 44, 4, 322-326 (1954).

9. H. R. Blackwell. "Studies of psychophysical methods of measuring visual thresholds." J. Opt. Soc. Amer., 42, 9, 606-616 (1952).

10. H. R. Blackwell. "Contrast thresholds of the human eye." J. Opt. Soc. Amer., 36, 11, 624-643 (1946).

11. D. J. Finney. Probit Analysis. Cambridge Univ. Press, Cambridge, 1947.

12. H. R. Blackwell. "Studies of the form of visual threshold data." J. Opt. Soc. Amer., 43, 6, 456-463 (1953).

13. H. R. Blackwell. Unpublished data.