Vision at Levels of Night Road Illumination

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SYNOPSIS

AUTOMOBILE driving at night is done with illumination of about 3,025 deg. Kelvin and intensities to give a brightness range of about 4 to 0.003 footlamberts. Within this range human visual power decreases in acuity, contrast, form perception, stereoscopic depth perception, the ability to judge size, motion and position and compensation to visual stimuli. Form and silhouette vision become more important than acuity, and mental and perceptual factors change at the lower part of this range. Changes of visual ability with age, specific factors of the eye, aniseikonia, adaptation, and general systematic factors affecting vision are summarized.

Within this illumination range eye changes from photopic (cone) to scotopic (rod) vision, which is important for estimating visual ability and the effect of colored lenses on vision. Positional and specific retinal effects and dark adaptation are considered.

New measurements are given for the effect of yellow glass, for acuity and contrast, and for night myopia obtained under conditions simulating night visibility.

Glare, or dazzle, reduces vision and the eyes should be protected from it, in so far as possible, by selective means which do not reduce the visual field, nor absorb any of the light needed for seeing.

Proper spectacles can improve vision for night driving for some people. When the light is focused exactly on the retina, the image is brighter, glare is reduced and vision is markedly improved. The best correction for after-dark seeing will usually be different from that for daylight use.

Some of the quantitative information on vision can be used in designing road markers for better visibility. After dark, vision on the highway is probably less good than it is in the laboratory and the data and criteria will have to be increased by a proper safety factor when applied to the highways used for night driving.

Visual training has improved night driving performance in the armed services and should be made a part of driving instruction and public education.

To see light, only enough intensity is required for a long enough time to stimulate the retina. To be visible as an object, it must have also sufficient contrast with its surroundings, and what is seen involves the distribution of light as an image on the retina, the sensitivity of the retina, the transformation of light energy to nerve energy, and the integration of the nerve impulses into consciousness in the brain. The spectral quality of the light and of the reflectivity of the object are important. Much is known about these processes at medium to high levels of illumination (25, 26, 38, 46, 96) and there has been considerable investigation of visual processes at very low levels of illumination (23, 42, 65, 75, 83). De Boer and Meulen (27) and Otero and Plaza (70) have summarized information at levels of night driving. Driving by civilians after dark is done with lighting between these levels and this paper will discuss and summarize some of the information pertinent to night driving.

ILLUMINATION RANGE OF NIGHT DRIVING

First must be known the amount of light available for vision while driving at night. It is obvious that it will diminish from daylight values to the very low levels found on a dark, rainy night. Considering the importance of the problem there are relatively few reports with quantitative data. A good example of usable information is Finch's (29) paper giving measurements made with fixed lighting on the East Shore Highway at Berkeley and on a 40-ft.-wide, gray concrete road as illuminated with high-beam and low-beam headlights. The luminance of the road with fixed illumination varied from 0.66 to 0.005 footlambert (ft.-L). With the upper beam the brightness of the road varied from 0.082 to 0.011 ft.-L. and with the lower beam from 0.07 to 0.02 ft.-L. A pedestrian in the outside lane 350 ft. away, dressed in a gray suit (reflectance factor, $\rho = 0.11$) had a brightness of 0.012 ft.-L. Luckiesh and Moss (59) found that highways and roads under moonlight have a brightness of 0.01 ft.-L. Bouma reports that most driving in the Netherlands is done at about 1 ft.-L.

To obtain local values, the author found that a cement section of parkway measured 0.12 ft.-L. with high and 0.2 with low beams and an asphalt section 0.16 and 0.12 ft.-L., respectively. Snow on a Stamford street gave 0.75 to 1.05 ft.-L. when illuminated by street lights of 1,300 ft.-L. brightness. Preliminary measurements are in general agreement with those of Finch and others and indicate the range of luminosity that should be examined.

Two cars were placed 200 ft. apart on the parking lot of the research laboratory on lines about 5 ft. from each other, simulating conditions on a narrow road. The luminosity of the gravelled-oiled surfaces within the beams of light varied from 3.4 to about 0.9 ft.-L. It was a cloudy dark night and the surrounding surface outside the beam was less than 0.01 ft.-L. On the black-top section, 1.2 ft.-L. were measured and the brightest region in both beams on the gravel was 6.3 ft.-L.

Holding the receiver of a Weston No. 603 foot-candle meter (with correcting filter) at the level of the driver's eyes the following amounts of light from the opposing high beam were measured.

Distance (ft.)	200	150	125	100	75	50	25
Foot-candles	0.2	0.2	0.3	0.38	0.4	0.55	0.7

Comparable measurements by Lauer (55) gave somewhat greater values to 2 ft.-L. In the beam from one car the road brightness and the brightness of a person dressed in brown (ρ = 0.03) were:

Distance ft.	Road ft.-L.	Person ft.-L.
25	0.34	0.48
50	0.52	0.15
75	0.08	0.03
100	0.025	0.016

This value found for ρ is less than the previously cited values of 0.11 for a gray suit, and Bouma's of 0.09 for clothing. Such low reflections must be considered in evaluating visibility on the highway.

Some of our measurements are higher than those of other investigators. The brightest values, of course, occur only in limited areas, but do contribute to the adaptation level of the eyes. The available data indicate that from 4 to about 0.003 footlamberts includes the average brightness range of night illumination available to automobile drivers. Higher levels give no concern, because seeing will then improve, but lower values will greatly increase the difficulties of seeing.

Knowing the range, we must next define the quality of the light. The 45-watt high beam of the General Electric No. 4030 sealed-beam headlight has a color temperature of 3,050 deg. Kelvin and the 35-wt. low beam is about 3,000 K. at 6.4 volts (1). For our purpose a color temperature of 3,025 K. may be taken as an average value to represent lighting from the automobile itself. In practice this will change with voltage variation. Because of the differential sensitivity of the eye, the color quality of the light must be known for proper experimentation and computation. More information is needed on the quality of road illumination.

Viewing motion pictures is a closely related problem and useful data gathered by their committees should be utilized. The problems of measuring motion-picture-screen brightness and highway brightness have much in common and meet at the outdoor drive-in theater (2).

Comparisons with other conditions of life are not easy. A room with the sun streaming in is bright and pleasant and part of it may be at several hundred footlamberts. At night with good illumination it also appears pleasantly bright; even when the brightness of walls may have only 7 to 10 ft.-L. The reason that both seem bright is due to the adaptability of our eyes. Toward the end of the day workers tend to turn on lights when the natural illumination reaches about 4 ft.-c. (92). For comfortable vision with small details, or with poor contrast, 20 to 100 ft.-c. are recommended by IES (46). White paper reflects about 80 percent, and newsprint 65 percent. Dark cloth may have a reflection of 4 percent, hence the above lighting would yield 4 ft.-L. when the 100 ft.-c. illuminates it. Yet we must see small objects of poor contrast when driving at night that may have a brightness of 0.01 ft.-L. This would be impossible were it not for the unique ability of vision to adapt over a large range of intensities. Seeing at night involves a good many abilities and limitations, some of which will be considered.

DARK ADAPTATION

The outstanding property of the eye is its great ability to adjust its sensitivity in accordance with the light reaching it. This adaptation may be measured as the least brightness perceptible. In the dark, adaptation occurs rapidly for a few minutes and then slowly for well over a half hour, indicating that two processes are involved.

The retina includes two kinds of light sensitive elements, the rods and the cones. Cones alone are concentrated at the optical center of the retina, the thinner fovea, and become less numerous toward the periphery of the retina. Rods are absent at the fovea and become more numerous toward the periphery. Color and best detail vision is mediated by the cones, and is absent at the outside of the visual field on the retina. Rod vision is more sensitive to low illumination. Foveal cones have single direct nerve connections; peripheral cones and rods have grouped connections. Vision is determined both by the composition of the area of the retina involved and the special properties of the light-sensitive elements.

Above a brightness of about 0.01 ft.-L., vision is mediated by cones and involves color. At high intensities the rods probably do not function, or may be inhibited by the cones. The lower level of cone vision is about 0.001 to 0.0001 ft.-L. Below this only rod vision occurs. The mesoptic region, involving both rods and cones, includes from about 1 to 0.001 ft.-L. For night driving we use mesoptic and photopic vision and are concerned with both systems at the critical change-over region.

Since human eyes vary in their sensitivity, it has been necessary to establish an average curve, called a standard observer, for use in problems of vision. At high intensities (more than 5 ft.-L.) the curve represents the cones and maximum sensitivity is found with yellow green light of 555 $m\mu$ wave-length, (Figure 1). At low intensities (0.001 ft.-L. or less) the curve for rod vision has a maximum near 507 $m\mu$ in the blue-green. Vision at the higher levels is called photopic and at lower levels scotopic. Over the interval that both rods and cones are involved, vision is called mesoptic. Between these brightnesses the curves for the sensitivity of the eye are intermediate. The gradual shift in the color sensitivity of the eye toward the blue is called the Purkinje effect. As the light intensity decreases reds appear darker and blues become brighter. At very low illumination color is not seen, merely lighter or darker grays. The curves of Figure 1 may be considered as the apparent brightness of equal amounts of light for the various colors.

Illumination usually does not provide equal amounts of energy for

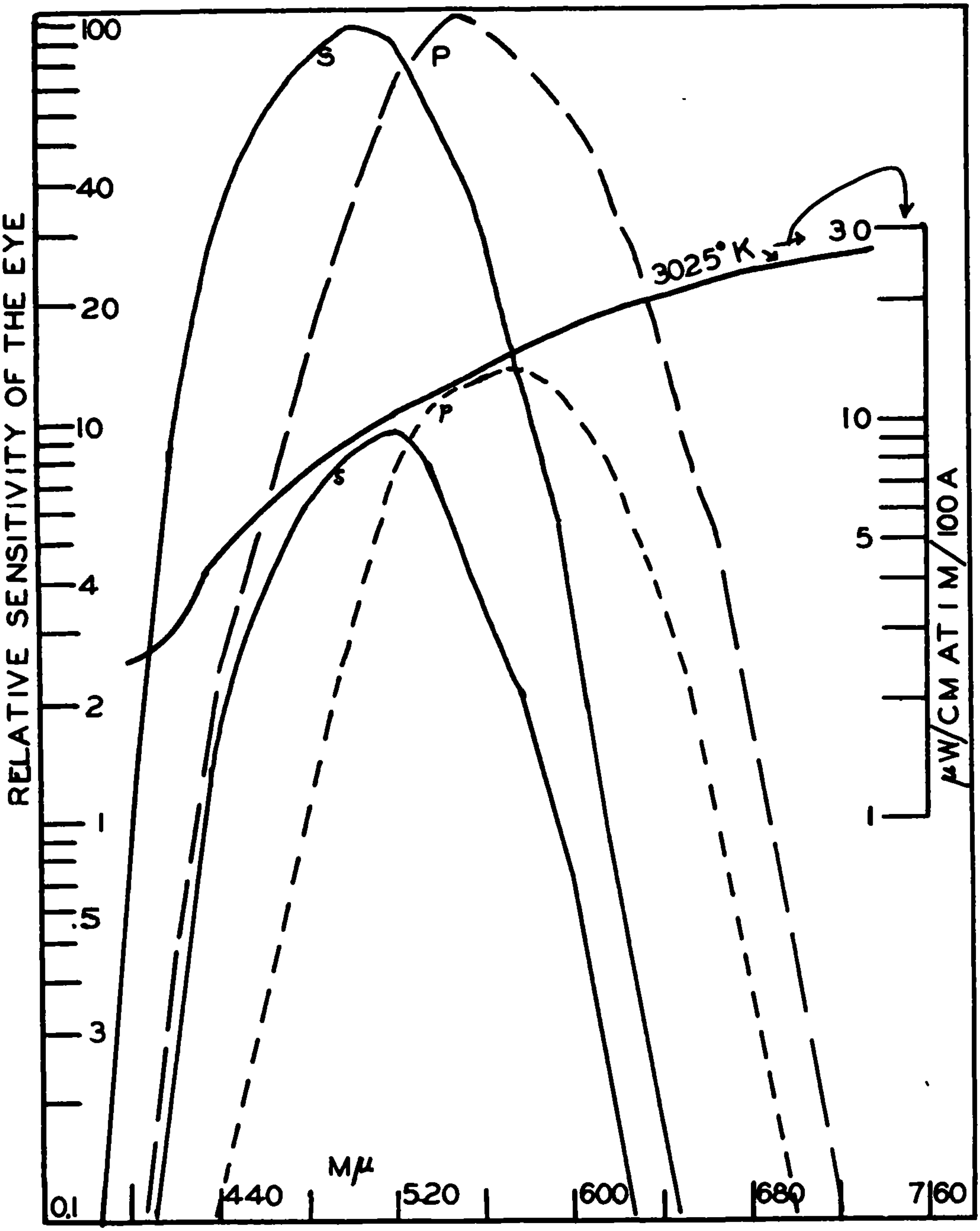

Figure 1. Relative photopic (P) and scotopic (S) visibility curves and their modification (p, s) by 3,025-K. light.

the different colors, e.g., tungsten light is yellower and redder than daylight. The energy distribution curve for tungsten at 3,025-K., representing automobile lighting, was obtained by interpolation from the data of Forsyth and Adams (31). The available energies were multiplied by the corresponding values of the standard observer to obtain the sensitivity curve of the eye with 3,025-K. automobile headlighting. By use of Weaver's tables (90) the sensitivity curves were obtained for the other lumination levels shown in Figure 2.

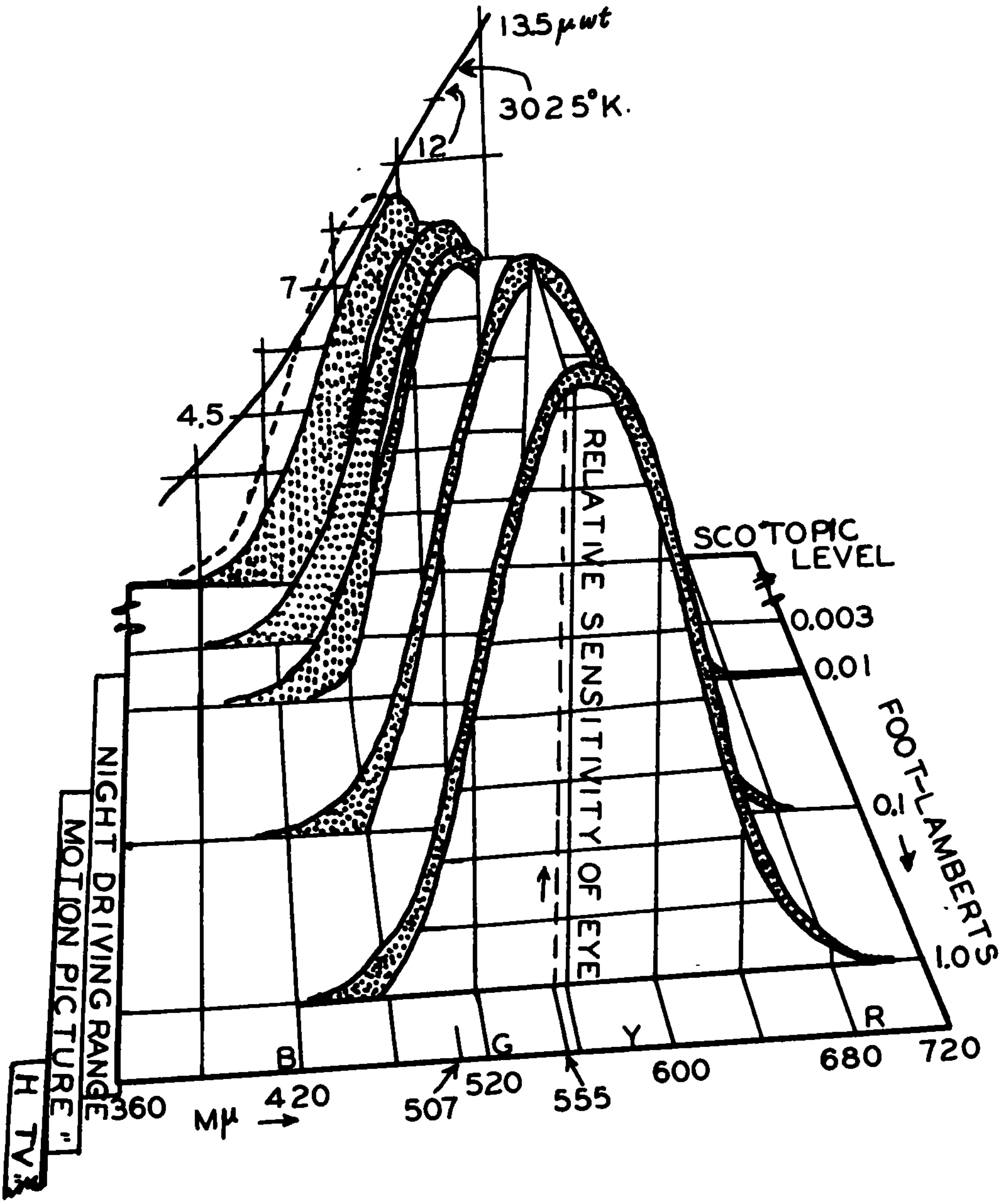

Figure 2. Shift of relative sensitivity of the eye toward blue as illumination decreases and the loss (shaded areas) from Noviol C yellow glass.

The greater amount of longer-wave-length light from tungsten flattens the photopic curve and shifts the sensitivity slightly toward the red. The Purkinje effect is shown by the shift of the maximum sensitivities toward the blue as well as the decrease in visual effectivenss of the light (decreasing area of the curves). Such curves are basic for the examination of many problems of vision. Taking the area under the eye sensitivity curve for 1 ft.-L. as 100, at 0.1 ft.-L. the area is 98 percent, at 0.01 it is 77 percent and at 0.003 ft.-L. it has decreased to 73 percent. The last curve on the model shows only 64 percent for the scotopic standard observer. The lessened sensitivity of the eye reduces the visual effectiveness of the available energy as well as shifting the color sensitivity of the eye.

COLORED GLASSES AND VISION

The model (Figure 2) is helpful for appraising the effects of colored glasses on vision. By multiplying the standard curves by the transmittance for a given filter, and plotting the resulting curve, the relative decrease may be demonstrated. This shows the futility of making comparisons unless the results are based on the radiation distribution being used. The average energy values for noon sunlight (5,400-K.) would have given different curves.

For example, the effect of a yellow glass will be considered. Multiplying the curves of Figure 2 by the transmittance curve of yellow Noviol C, reduces each by the amount indicated by shading on the curves of the model. (In anticipation of this application the standard curves had been reduced for the losses from the two surfaces of the glass to provide comparable data.) Examining the areas under the curves as indicative of overall vision predicts a 6 percent loss at 1 ft.-L., 10 percent at 0.1, 15 percent at 0.001, and about 20 percent at 0.003 ft.-L. Similar computations could be made for any other color. All colored glasses selectively absorb more or less light and the amount vision is affected depends on the radiant energy available, the overall transmission, the color transmitted, and the Purkinje shift. How much loss of vision may be tolerated in night driving remains to be decided.

The sensitivity curve for the eyes of an individual may be different than the average taken for the reference curves and may depart considerably when color deficiency or color blindness is present and such curves illustrate the nature of visual aberrations (94, 96). The standard curves are useful for general appraisal, but for an individual only the individual curve should be used.

Two questions are of interest with respect to the use of a yellow glass for night driving: (1) what is the effect of the yellowness itself, and (2) what difference occurs between wearing yellow glasses and no glasses. These can be investigated using either light from automobile headlights or light adjusted to the same energy distribution with proper color temperature adjusting filters. Such a projector was used in my laboratory to illuminate an acuity test chart (American Optical Company's No. 1930) and a Luckiesh-Moss, calibrated contrast chart (General Electric Company). After a preliminary check with room illumination at 10 ft.-L. for any unusual visual inability, observations were made at 20 ft. distance with 1, 0.1- and 0.01-ft.-L. chart background brightness. Viewing conditions were comparable to driving in that the charts and their surroundings were lighted and the illumination fell off from this region in all directions. Observers wearing spectacles for night driving used them in the tests, otherwise no glasses were worn.

Acuity and contrast were measured at each level of illumination with the Noviol C yellow glasses, without them, and without them at an intensity reduced by 15 percent with a neutral filter, to match the 15 percent overall absorption for the yellow. Comparing the results with the yellow glasses and without them at the same visual intensity of lighting gave the answer to the question as to the effect of yellowness. The other comparison showed the gain or loss between wearing yellow glasses and not wearing them.

The data for the first 30 individuals tested (ages 16 to 56) are shown in Figure 3. For yellowness (yellow versus direct light less 15 percent) we find few gains, more loss and most observers showing no significant differences (greater than $\pm$ 3 units) for both acuity and contrast tests. At the lower intensities the loss of visual power was greater. The actual test results support the predictions from the knowledge of vision as expressed in the model of Figure 2.

A large number of the observers could see no better or worse under these conditions with yellow than without yellow glasses. There were more showing less good vision than better vision with yellow. The individuals which gain with yellow may have personal deficiencies in color vision, or a strong liking for yellow, and will be tested further. The comparison of wearing yellow glasses against not wearing glasses demonstrated a much greater loss of acuity and contrast vision from the yellow glasses and the details of this investigation will be reported on its completion. (See also Sections 4 and 7).

Colors affect people differently and these psychological factors must also be considered in night driving evaluation (8). For some, yellow glasses brighten the world, give a sense of euphoria, and they may believe that they are seeing better, even when the test scores show the opposite. Other people cannot tolerate yellow. Roper (3) states that yellow becomes increasingly uncomfortable for some people once the car is in motion. Does the favorable effect of yellow on some extroverts make for more alert, better driving, or does this effect lead to overconfidence and a tendency to take chances? Examination of accident records might provide an answer.

Haus and Cole (44) in a preliminary paper suggest a gain from yellow night glasses in reduced glare, increased comfort and confidence, and reduced fatigue. They used a yellow that transmitted ".1 percent more yellow than ophthalmic crown." Since the transmittance of ophthalmic crown for yellow is limited only by the surface losses, it is difficult to understand their statement unless they used a coating to increase the transmission. Their values of 580 $m\mu$ for optimum photopic and 530 $m\mu$ for scotopic vision are much higher than generally accepted, and it is believed unlikely that their yellow evades the Purkinje shift as they suggest. It is to be hoped that these discrepancies will be clarified when they present their detailed report.

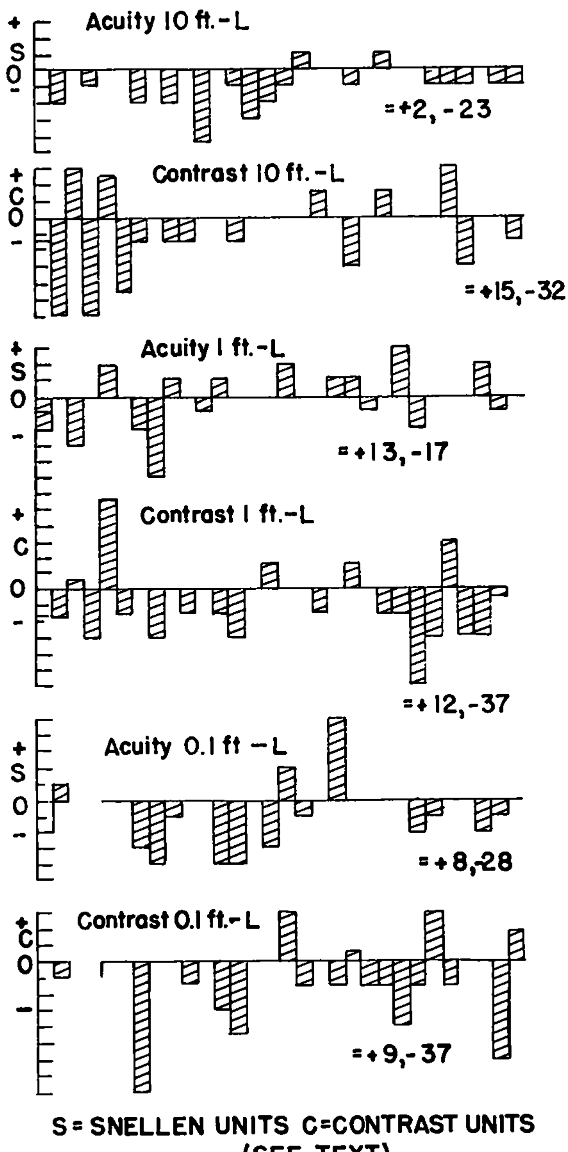

Figure 3. Effect of yellow on the ability to see contrast and detail at different brightness.

Other arguments have been presented in favor of yellow night-driving glasses. Yellow, by absorbing the blue light, is said to reduce the chromatic aberration of the eye, compensate for some of the night myopia, and lessen the effect of haze. Haze scatters light, especially the shorter-wave-length light, but in daylight outdoor tests yellow and other colored glasses have not been found helpful (64A, 87A). Haze and opacities within the eye decrease vision and are especially bad in scattering light as with glare from opposing headlights. Tests with such pathological conditions should be made. Since the eye, in contrast to the photographic plate, is less sensitive to blue, violet, and the long-wave-length ultraviolet, one should not expect a similar gain from a haze filter.

With low illumination, color becomes less important and a corresponding reduction of chromatic aberration may occur. Correcting the chromatic aberration at high intensities has not given greatly improved vision. The eye apparently compensates for these differences, and with considerable limits, to others that may be added, according to Hartridge (38). Changes in apparent brightness with decreased intensity of lighting reported by Bouma (13) for sodium-yellow-lighted roads, fails also to support such a theory as it is a monochromatic light for which there would be no color aberration. Although elsewhere (12A) he states that blue light contributes more to glare and that yellow light is less glaring.

Should yellow compensate for part of the night myopia, less correction should be required and visibility would be correspondingly better at lower levels. The first 30 individuals of the test series reported here gave no evidence to support this premise. Until adequate evidence is forthcoming to support these theories, there seems to be scant use for citing them as possibly favoring yellow vision.

With the exception of such general statements, the author has been unable to find any proof of gain in night vision for any large number of people from yellow glasses. Since such a gain would be contrary to much known visual experience, any proof must be supported by careful, critical experiments. On the other hand, experiments by Lauer (52, 53) and other investigators reveal a loss in vision when colored glasses are worn at the illumination levels of night automobile driving.

ACUITY AND CONTRAST

Other aspects of vision at levels found during night driving are summarized in Figure 4. The amount of increase in brightness to be noticeably brighter (Δ B/B) is a constant over considerable range until the intensity is lowered to about 1 ft.-L., Figure 4A. For lower brightnesses, the Weber fraction (Δ I/I) and the Weber-Fechner law no longer apply and discussions involving them are apt to lead to confusion. The progressively increasing brightness is different for white and colored lights. At the lower levels the illumination has to be considerably increased to appear brighter, and this is another measure of the difficulty of seeing at these levels.

While acuity is sometimes used to summarize the many aspects of vision (51), the physiologist restricts it to the ability to see the least visible, the least separable (resolution), or the least legible. Different tests are necessary and the results obtained depend on the test, the procedure, and the criterion used. Figure 4(c) gives the curve obtained by Lythgoe (61) for acuity as measured by the ability to see the gap in a Landolt C using an end point of 4.5 correct answers in each 8 answers for each test. The reciprocal of angle subtended at the eye by the gap is plotted. Earlier acuity measurements of König are included also. To be seen equally well at 0.01 ft.-L. a test object of high contrast must be about four times larger than it needs to be at 3 ft.-L.

Luckiesh and Moss (59) tested a group of people at 10 and at 0.01 ft.-L. Of 150, they found 117 to have 20/20 vision at 10 ft.-L., but at 0.01 ft.-L. the highest was 20/38 for only 11 individuals, and the median value was about 20/55 for the low contrast test chart used. Lauer, et al (54) demonstrated that some high-contrast test charts are more legible than other charts.

Contrast is the difference in brightness between a specimen and its surroundings. It is expressed numerically as the difference in brightness of background and specimen divided by the brightness of the background, and is often converted into percent, (See Figure 4(c)). The lower the brightness, the greater must be the contrast of the test object for it to be visible. Over the night driving range shown, contrast must be increased from 6 to 20 times to remain visible, depending on the background being lighter or darker than the object. When the contrast is too low, a pedestrian or other obstacle cannot be seen. Unless the contrast of a marker is adequate for its size, it may not be legible long enough to be read by the motorist. Recommendations made for the contrast concerning motion pictures (35, 56) are suggestive for road lighting. Blackwell (11) has published contrast lumens for a test object subtending 24 minutes of arc at four levels of illumination. Information units gathered by the eye also decrease in a comparable manner at corresponding lighting levels (47).

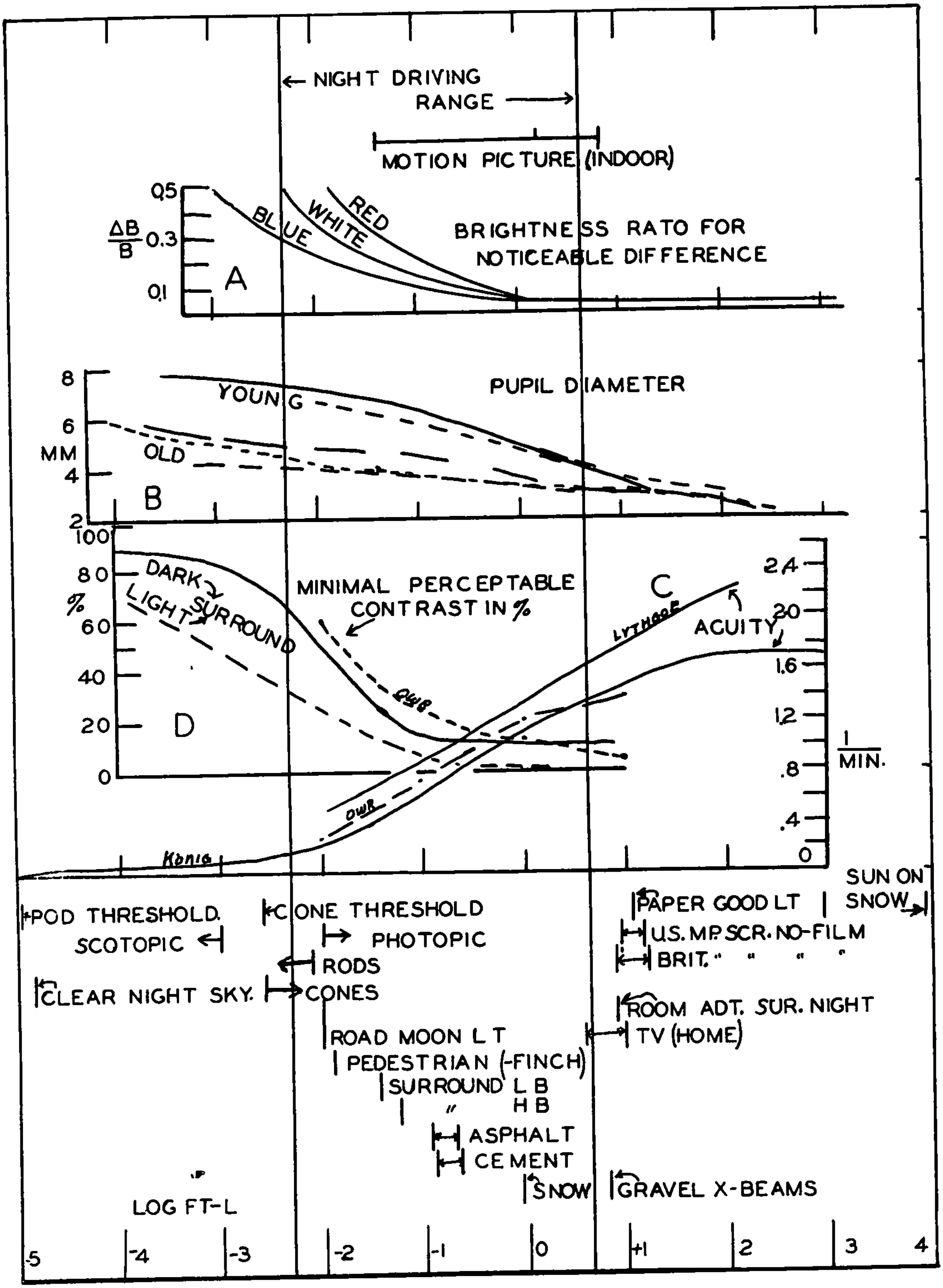

Figure 4. Night-road-illumination values and some aspects of human vision with decreased illumination. Limits of photopic and scotopic vision are located as reported in the literature; although they are actually regions of transition.

Using the equipment that was described briefly above, measurements were made of 30 individuals for acuity on the letter test chart and for contrast with the contrast chart. Taking the averages, gave an acuity (Snellen nomenclature) of 20/15 at 10 ft.-L., 20/18 at 1 ft.-L., 20/29 at 0.1, and 20/84 at 0.01 ft.-L., which correspond to acuity values of 0.8, 0.9, 1.5, and 4.2 minutes arc subtends. This series has an excess of slightly far-sighted observers and as those needing glasses were well corrected, the average is somewhat better than the usual normal. The minimum contrast seen on the Luckiesh-Moss calibrated contrast chart for the same illumination levels were, respectively, 4.8, 11.3, 25, and 60 percent. The data were obtained in my laboratory under illumination conditions comparable to automobile headlighting, Figure 4, and are consistent with the other curves in emphasizing how vision decreases as the illumination and brightness decrease even over the illumination range of night driving. An increase 5 times in the size and a 12 times increase in contrast is indicated to obtain the same visibility for markers at 0.01 ft.-L. as at 10 ft.-L. When glare is also involved these values may be still greater.

At low intensities the area of the test object affects its visibility as shown by Hanes (37), and Casperson (22). Hoppe and Lauer (45) are measuring this factor with respect to the visibility of autos on a highway. There is evidence that there may be a critical level around 0.02 to 0.05 ft.-L. for visual performances involving more than a yes-or-no response according to Rock (77), and Spragg (87). Seeing at night on a highway depends mainly on silhouette seeing (27, 78), therefore contrast and area become more important than acuity. The visibility with sodium- and mercury-arc lighting of highways has been discussed in terms of contrast and color contrast by Bouma (13, 14).

Both contrast and acuity have been shown to change with the illumination and the measurements can be plotted on three-dimensional figures to give a more complete picture (32, 60). Weston's (91) equation for illumination and contrast might be another point of departure. Older people require more light and even with maximum illumination do not see as well as younger ones (92A). Such information on average visibility can form a basis for design of signs and protective markers, but cannot be used directly as vision is probably less good at night on the road than it is in the laboratory. Some of the differences have been discussed by Bouma, Lauer, and Roper. Appropriate safety factors should be obtained and used. In the meantime Finch's (29) multiplying factors seem reasonable.

SPEED OF VISION

In addition to sufficient light and contrast, the image must last on the retina long enough to initiate nerve action, otherwise vision will not occur. The lower the illumination the longer the light stimulus must act to be effective. The highway marker may not be seen long enough to be understood. Roper and Howard (78) report a loss of 20 ft. in distance vision for an increase of 10 mph. Time factors are important and become more so as the intensity of illumination decreases. The ability to judge motion decreases 66 percent to 75 percent (Hodel-Boos, (40).

A short flash may raise slightly the sensitivity of the entire retina. A second image falling onto the retinal elements during the refractory period after a previous stimulus will not be registered. After-images have a regular time series and a pedestrian cannot be seen when his image occurs on the same region of the retina that has an after-image from a bright sign or has been strongly stimulated by a glaring headlight. A brief summary of these relations can be found in Davson (26). Older drivers see and react less rapidly than younger ones. The threshold for movement discrimination increases logarithmically as illumination decreases linearly.

Less is known about the effect of time at the levels under consideration and this should be a good field for investigation. Either markers should be simple, large, with high contrast and good brightness for parkways permitting fast night driving, or driving rates should be scaled down to within the abilities of the driver.

SPECIFIC FACTORS - THE EYE

External eye. Muscle coordination should be good and the best possible correction for phorias should be given to the person requiring spectacles for night driving. Astigmatism becomes much more important when illumination is less as the distorted retinal image is more difficult to interpret. A cylinder of 0.25 D in the correct axis may improve vision from 6/8 to 6/6 or 25 percent according to Hamburger (36). Convergence is not as well stimulated by dim illumination and stereoscopic vision might well be studied at night-driving levels of illumination, since relative motion, position, and distance judgments are of importance when passing.

When the eyes are blinked, vision is not possible for the 0.3 sec. the eyes are closed and is impaired for part of the closing and opening periods for an average blackout period of about 0.55 sec. (38). The time between blinks averages 2.8 sec. for men and 3.8 for women. Other blink types with longer interblink periods are known and much individual variation is found. The loss of vision in such a blackout period could cover some 60 ft. of travel at 40 mph. to 90 ft. at 60 mph. Should the blink come at a critical time, and blinking cannot be delayed indefinitely, it might cause an accident.

With fatigue, blinking increases and more vision time is lost. Luckiesh earlier suggested that the blink rate might be measure of fatigue, but a quotation by Hausner (39) implies that it may be more of an indication of tenseness or strain.

Internal eye. Changes in the interocular pressure interfere with vision and certain diseases may disqualify a person from night driving. Changes in the absorption and transparency of the components of the eye may reduce night vision proportionally more than day vision.

Age changes in accommodation are important both in focusing and in a diminished reserve, (Figure 5). Duran (28) has demonstrated a decrease in accommodation range with decreased illumination with the midpoints becoming more and more minus until at very low intensities the focusing mechanism fails, leaving the lens focused at about 32 in. according to Otero and his colleagues. There is some question to the exactness of this

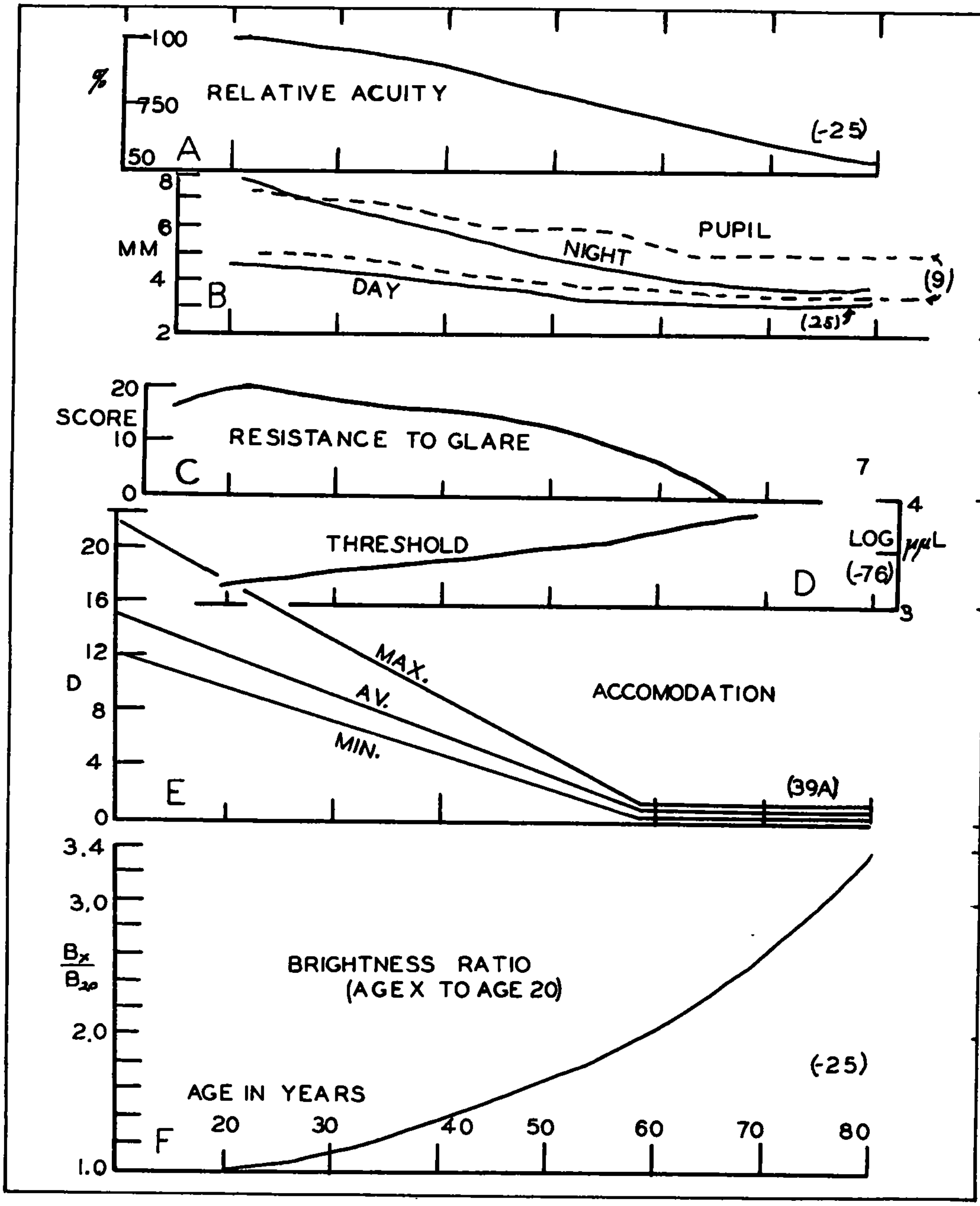

Figure 5. Changes in human vision with age.

conclusion (49), although it is incorporated into the 1950 recommendation of the International Commission of Optics (J.O.S.A. 40:881). This decrease of accommodation may be the source of a considerable part of night myopia.

The pupil diameter increases, as the light intensity decreases, (Figure 5), but the increased diameter becomes progressively less with advancing age. Measurements by Birren (9) show that the pupils of older eyes contract relatively as much as pupils of younger eyes. Some recent study suggests that the pupil does not increase continuously but shows a fast maximum of 5.5 mm at 3.0 to 0.3 ft.-L., a second of about 4.5 mm at 0.5 to 0.03 ft.-L. and then a gradual increase to 8 mm (69). The time relations of these changes as seen on Cabello's (20) curves are of importance in nocturnal vision. The combined effect accounts for the increase in the threshold of vision with age, according to Robertson and Yudkin (76). More illumination is necessary with older eyes to give a just noticeable difference for brightness at a given age to brightness at age 20. Retinal and other changes must be involved as the retinal illumination control by the decreasing pupil expansion does not explain the decreased resistance to glare found in older ages. The increase of the pupil diameter allows more of the edge of the lens to be used and increases spherical aberration; but Otero and others do not believe the small increase ($\pm$ 0.3 D) in spherical aberration to be very important in night vision. However, the writer believes that it might be more important in naked-eye than in instrumental vision, as it is a cause of unsharp retinal image, equivalent to an appreciable loss of image intensity. Chromatic aberration of the lens is also involved.

Local retinal effects. Vision is partially controlled by the form, the chemical and physical organization, and function of the retina. These factors must be kept in mind in evaluating specific seeing tasks and will now be considered briefly.

Recovery of rods and cones involves bodily metabolism and the greater the bleaching from intense stimulation, the slower will be the recovery. The rods recover more slowly than the cones, which may be one reason for the suppression of rod vision at higher intensities.

Adjacent regions of the retina do affect each other. Juxtaposed surfaces may increase or decrease the apparent contrast of each other, both in color and in brightness from simultaneous contrast. Likewise, areas of equal size, white-and-black-checker pattern, will not appear equal, especially as illumination is decreased due to induction and radiation effects (97). Intense glare may desensitize some of the nearby retina.

Spatial summation depends on how the retinal elements are grouped and interconnected. The rods are connected to the nerve cells in varying-sized patterns and numbers. Thus large fields are prejudicial to acuity, but favor threshold sensitivity and this may explain some of the area effects observed at low brightnesses.

The sensitivity of the retina is highest in the fovea and least at the periphery. Vignetting lessens efficiency for areas beyond about 20 deg. from the fovea. At the night-driving range these factors become important and must be considered. With a one-eyed person a small object may be imaged on the blind spot and not perceived. Objects seen with one eye appear about 60 percent as bright as when seen with two eyes (74). Tests for night vision are discussed by Holmes (42A).

Dark-Adaptation Modifiers. Exposure to sunlight decreases the ability for dark adaptation and Clark et al (24) reported that eyes exposed to strong sunlight, as at a beach, required 90 min. longer to reach the same level of dark adaptation as eyes not so exposed. Protection from sunlight during the day with proper sunglasses improves night vision (98).

Smoking also decreases the ability to dark adapt, presumably from the carbon monoxide rather than from the nicotine content of the smoke, although the evidence is conflicting (63, 84). Lowered oxygen pressure as at altitudes of 8,000 feet or more decrease night vision.

Caffeine, metrazole, strychnine, ephedrin, octin, excessive Vitamin A, muscular exercise, ultrasonic vibrations and stimulation of taste failed to impair or improve night visibility (80). Benzedrine, breathing increased oxygen, or breathing more rapidly and deeply, aid dark adaptation. The lack of drug effects led Mandelbaum (64) to conclude that no central nervous function was involved. Moderate consumption of alcohol can raise the threshold 0.3 log unit, but the gain is offset by the adverse effect of alcohol on judgment and motor response.

Dark adaptation is reduced by a deficiency of Vitamin A, a chemical used in the retina as part of the visual process (30). A deficiency of Vitamin A may be due to: lack of the vitamin or the provitamin in the diet, diseases preventing absorption in the intestine (diarrhea), resulting in a decrease of biliary or liver secretion, of the liver preventing storage or conversion, the capillaries of the chorioid, pigmented epithelium, bacillary layer of the retina, causing high usage of Vitamin A such as fevers and hyperthyroidism, increased basal metabolic rate, chronic alcoholism, or from rapid growth or pregnancy. Stern (87) estimates that two thirds of the Americans in low-income groups are deficient in Vitamin A. Miners have a condition of raised threshold or impaired dark adaptation that Campbell and Jenks (21) could not relate to their nutrition. Deficient rod adaptation is a probable explanation for hereditary night blindness. Fletcher (30) mentions a series where it was traced for ten generations.

Exposure to the ultraviolet from a fluorescent lamp delays the shift to rod vision several minutes and prevents the dark adaptation to reach as low a level of sensitivity by about 0.3 log units as shown in Boeder's summary of Wolf's work (10B, 93). The delay suggests a longer wait outdoors in the dark before driving when one has been exposed to long-wave ultraviolet. To what extent the change in adaptation level affects vision at night-driving levels must be investigated. Tungsten does give off a small amount of ultraviolet radiation at 3,000 K. Windshields are transparent to this radiation (about 75 percent at 365 $m\mu$) as measured by R. D. Hudson. The amount of radiation may be too little to affect night driving, except when the glare is nearly continuous as on roads with nearly constant opposing traffic.

NIGHT MYOPIA

That the eye becomes near-sighted in dim light has been known for about 70 years. Little investigation occurred before World War II, which was followed by considerable literature that has been summarized by Koomen (49) and others (6, 70). The myopia found has ranged from 0.4 to 4 diopters, depending on the illumination levels and methods used.

Two main theories have evolved: Otero and his colleagues attributing part of the effect to spherical aberration (0.25 D), part to chromatic aberration and the rest to decreasing involuntary accommodation; while Koomen's group account for night myopia by the uncorrected spherical and chromatic aberrations of the eye. There is considerable disagreement and more work will be required for a final answer as to its cause.

According to Cabello (20) night myopia increases rapidly for the first 5 minutes to about $1\frac{1}{4}$ D., remains fairly stationary for 5 minutes and then increases slowly to reach final equilibrium in about 20 minutes.

When night myopia is corrected, both Otero and Salaverri (71) and Wald and Griffin (89) point out that the same degree of vision could be obtained with half the light because of the greater sharpness and efficiency of an infocus image.

Byrnes (19) stated that: "This 'night myopia' does not apply above rod levels of illumination. For this reason the suggestion sometimes made that spectacles for night driving be made 0.5 diopter more minus than the regular distance correction is not justified. The 'night myopia' only occurs in average persons while rod vision is being used when the light is below the level of moonlight."

Schoen (82) demonstrated night myopia by skiascopy and found that at lower illuminations the image was in the vitreous in front of the retina, thus adding objective support for night myopia. He found -0.5 D at 0.01 ft.-L. and -1.62 at 0.0001 ft.-L.

Pratt and Dimmick (73) have analyzed and published Bruger's work on 558 young naval students. The data are grouped by the amount of refraction necessary to give normal vision. They found the eye more myopic at lower levels of lighting and that acuity decreased from 1.0 at 2 ft.-c. to 0.12 at 0.0027 ft.-c., for the group farsighted to the extent of +0.75 at the higher intensity. Daylight acuity tests are adequate for screening the poor night vision group according to him.

Hamburger (36) reported no correlation between night myopia and high myopia at daylight levels of illumination. The increase of night myopia with some very near-sighted people may be related to poorer function of the cones, less active accommodation and possibly a less active pupil function.

Sasian (81) found that a simple hyperopia of +1.8 to +2.0 will neutralize a night myopia of -2 D, but that other types of hyperopia will not do so.

A study is under way in my laboratory to determine the extent and effect of night myopia. Parts of the associated preliminary work on acuity, contrast and yellow have been considered in this paper previously. Using a modified phoropter, the lens additions needed to give best vision were determined subjectively. The differences between the acuity and contrast scores with and without the additional power correction measure the night myopia. The average acuity and contrast were 20/18 at 1 ft.-L. and 11.3 percent. Correcting to best vision with additional minus lenses gave a respectively 20/15 and 8.8 percent. At 0.1 ft.-L. the corresponding values were 20/29 and 25.4 percent, correctable to 20/26 and 20 percent. At 0.01 ft.-L. correction improved acuity from 20/84 to 20/70 and contrast from 60 to 40 percent.

The results indicate that significant improvement in vision may be obtained with additional power corrections of from -0.25 to -1.75 D. Some far sighted people (+0.5 D) without astigmatism see better at night without their spectacles. Loss of any astigmatism correction, however, may be greater than the gain from night myopia and such correction spectacles should not be removed.

Some near-sighted people have greater night myopia, because they lack this plus reserve and may be undercorrected as well, even at daylight levels. Properly determined night glasses (no color) have improved the after-dark driving ability of individuals. The results given are only averages and uncorrected for age effects. As soon as sufficient data are available, a detailed analysis and recommendations will be published. The preliminary results suggest that vision after dark for certain drivers may be markedly improved and that should make for better driving on the highways.

ANISEIKONIA

Binocular vision is impaired for some people because the images have different size and do not fuse to give normal space impressions. The general complex of symptoms: headaches, car sickness, photophobia, blurring of vision and incorrect spatial localization, increases fatigue and lowers efficiency. The specific visual difficulties make driving through narrow spaces, such as narrow roads, garage doors, and traffic jams very difficult and hazardous. Continued scraping of fenders may be due to this kind of faulty vision. Measurement and the proper glasses are known to improve driving ability in close quarters. Aniseikonia may be a greater handicap after dark and it should be investigated as part of the study of people having repeated accidents. Boeder (10A) has described the space problems and their measurement for this abnormality of vision.

GENERAL FACTORS - SYSTEMATIC

<u>Sex</u>. No improtant differences have been discovered in night vision between men and women.

<u>Individual variation</u>. Average day-to-day variation in adaptation levels amounts to 0.2 log units for cone and 0.3 for rod vision. In a healthy individual the variation may be somewhat less; between individuals somewhat more. Lythgoe (61) has discussed variation in visual acuity and precautions necessary for its control.

Diseases have pronounced effects on vision. Some diseases of the eye such as glaucoma, changes in the retina, or detachment of it may decrease vision until blindness occurs. Deficiencies of Vitamin A, riboflavin, thiamine and possibly others diminish vision. Diseases known to affect vision are: urinary calculus, cirrhosis of the liver, and diabetes. Pregnancy causes temporary changes in the retina.

Seasonal. Vision is better in October and poorer in January.

Age. Senescence is a gradual deterioration that starts shortly after fertilization and involves the eyes as well as other parts of our bodies. Some of the more pertinent changes are shown in Figure 5. Accommodation, pupil size, resistance to glare, all decrease the threshold at minimum level increases, and it takes a proportionately greater increase in illumination to give a just noticeable increase in sensation. A pedestrian barely visible to a young eye cannot be seen by an old person. This is an important consideration in evaluating any spectacles of colored glass which would decrease the amount of light to the eye. The transparent media in the eye, especially the lens and vitreous, tend to increase in absorption and may become partially or wholly opaque. Thus any screening program must be capable of discovering such changes. The average curves of Figure 5 must not be used for an individual as some persons have younger eyes in older bodies or vice versa. Proper tolerance ranges will have to be established.

Fatigue. Fatigue occurs with decreased, flickering, unsteady, or varying light. The pulse rate may slow so that less oxygen and nutrients reach the visual mechanism. The blink rate increases giving more blackout periods. Using more than half the accommodation reserve increases fatigue which may be a factor for the older driver whose accommodation is below the needs of the road with night illumination. General bodily fatigue also decreases vision. At night there is little to see other than the small part in the headlight beam. A small region of the retina is used continuously as there is little stimulus to look away and rest the eyes. Also there is less tendency to change bodily position. These may lead to so-called self-hypnosis and loss of consciousness thought to be a factor in single car accidents. Checking the instruments on the dashboard is more difficult than with day illumination and gives added fatigue to the uncorrected presbyope.

Human engineering is concerned with "skill fatigue" with reference to airplanes and MacFarland's (62) summary could cover auto driving as well. The onset of skill fatigue shows: (1) inaccurate timing of control movements, (2) a tendency to require larger changes in stimuli to initiate action and (3) a lessening of the normal span of anticipation. There is an increasing awareness of bodily sensation,hyper-reactivity to machine and people, and small items begin to dominate and prevent reaction to a pattern. The tired night driver thus needs increased stimuli or more light in order to see equally well and a longer warning period before he is required to act (stop, turn, etc.). Since it is not possible to do all this for the tired driver—it should not be surprising that accidents increase. Night warning signs should be placed further from the reference and, if possible, brighter as increasing size beyond an optimum has not been found to increase visibility.

Possibly the only night-driving situation that is not more fatiguing is driving on long stretches of nearly straight road with a minimum of traffic, as may be experienced only in sparsely populated regions.

Psychological factors. Alertness, attitude, and enthusiasm are important in night driving. Anxiety states depress this ability. Roper and Howard (78) have called attention to the more-rapid perception of an obstacle when it was expected than when it was not anticipated. Unusual interest may overcome partial fatigue or delay its onset. Self-hypnosis may be a factor in night driving accidents.

Night blindness. Night blindness with inadequate dark adaptation occurs in a few people who are unable to see well at low levels of illumination. This may be hereditary and permanent, or temporary due to a nutritional deficiency, or to the results of infection or disease. Little can be done for permanent cases, other than restricting their driving to daylight or their speed after dark. The temporary cases are clinical problems, but their existence should be considered in any screening or evaluation program.

All of these systemic factors are vague in the sense of not being quantitative or fitting into a night driving personal equation. However, they are included here to serve as a warning, and a check list for the effectiveness of any program and as problems for investigation.

GLARE

The IES Handbook states: "Disability glare sources, by increasing an observer's adaptation level, reduces his contrast sensitivity as the contrast between a visual task and its background or both.... Disability glare is present whenever a source of higher brightness than that of the task is superimposed on the surround." Various theories are given to account for discomfort glare. Glare has the effect of a veiling brightness, Bg, = $23E/D^{1.8}$ where E is the illumination at the eye from the glare source, D is the angle it makes with the line of vision, it is equivalent to a change of adaptation to higher level and the eye then cannot distinguish as small differences in intensity.

Marked differences in contrast as 50:1 are unpleasant. Holladay (41) Luckiesh and Holladay (58), Luckiesh and Guth (57) and others, have devised methods for the analysis of glare and the conditions where glare becomes intolerable.

The effect of glare on the retina depends on whether it is diffuse or concentrated within a small area. Even in the latter case there may be some diffuse or scattered lighting of more or less of the retina. When the intensity is considerable, the reserve of materials for regeneration of the sensitive chemicals in the receptors may be depleted and vision greatly reduced for a period of time. A large response in a glare area may inhibit smaller responses of nearby retinal areas due to interactions in the electrical phenomena of the nerve fibers. A concentrated glare area may produce a halo from scattering that will reduce visibility in nearby regions but that will not reduce absolute brightness. Glare causes a change in adaptation, thus tending to reduce its own apparent brightness. Any opacities in the ocular media will scatter light and cause veiling glare (94).

Glare in night driving varies from a quick passing through an opposing light beam to rapid, and successive exposures to the lights of opposing cars on a heavily traveled road, e.g., driving on a narrow parkway in the direction opposite to the main traffic flow. In the latter case the glare causes more fatigue, but is less dangerous as the eyes are kept on a higher adaptation level, than does sudden blinding of nondimmed high beams of a lone car when the eye is adapted to a lower level of illumination. After-images from glare sources may prevent vision in that part of the retina. Glare is not often reported as a cause for accidents (4).

Little study has been made on recovery from glare. Presumably the pupil contracts and then enlarges and such pupil changes are usually fairly rapid. (Contraction to minimum in 5 sec. Increase of 1 log unit above threshold brightness required,88). The rate of recovery depends on the amount of glare (time and intensity). On a trip from Southbridge to Stamford the exposure to passing glare averaged about 2 sec. per car and the brightness of the headlights appeared to average about 500 ft.-L. with extremes of 200 and 3,750 ft.-L. The higher levels were very uncomfortable. As the measurements were made within a moving car, their precision may not be high. Glare is reported to affect the accommodation mechanism (72). Younger subjects are unaffected, but in the older ones, there was a lengthening of the accommodation near point. No effect was found with aphakics. The result was believed by them to be due to the stimulus from heating of the lens by the extra light.

Lauer and Silver (55) investigated vision against opposing lights with a Ferree and Rand acuity meter used as a projector, of 0.25 to 2 ft.-c. and the affect of angle of view as 1 ft.-c. With an opposing beam at 3 deg. of 1 to 2 ft.-c. the required light to see was $y = 0.0556x - 0.1412$, where x is the standard of visibility required. For 100 percent acuity and the opposing light in ft.-c. the light required for seeing is $y = 4.112x - 1.112$, or the light to offset 0-1 ft.-c. of opposing light. The greatest relative effect of opposing light was found at 5 deg. and the greatest absolute effect at 3 deg. from the line of sight, twice as much light is required for observers of 70 percent acuity (20/60) and 1 ft.-c. opposing light requires 10 times as much light to see as well as without the opposing light. Dark objects required 4 times as much light to be seen as do light objects. They reported that the visibility threshold for an 8 percent object is increased 28½ times for opposing light of 1 ft.-c. at 3 deg. Depressing to the low beam decreased the opposing light to 0.2 ft.-c. and the glare about one fourth. Lauer and Silver found further that the color threshold was 75 times greater than the visibility threshold. Fortunately avoiding obstacles in night driving does not require seeing what color they are.

Finch (29) made the only attempt the author has found to evaluate quantitatively night driving lighting. For a low beam the average illumination on the road was 1 ft.-c. and with the reflection for oil-stained concrete taken as 0.10 the adaption field luminosity was computed to be 0.08.L. per sq. ft. Referring to Konig's acuity data, this minimum contrast is 0.035, indicating that the average observer would detect a difference in brightness of 3.5 percent and could correctly identify a brightness difference of 3.5 percent about half of the time. For the upper beam the illumination on the road was 1 ft.-c. at 50 ft., 0.05 at 100 and 0.07 ft.-c. at 200 ft. The adaptation luminosity was 0.042 ft.-L. and minimum contrast 0.05, nearly twice that of the lower beam. For comparison, the adaptation value of an average room lighted with 20 ft.-c. was found to be 7.5 ft.-L. and the minimum contrast was 0.01. Visual acuities then are for the room 1.6 (0.6 ft.) high 0.55(1.8 ft.) and low beam 0.75 (1.3 ft.). A pedestrian 350 ft. ahead in the outside lane in a gray suit would have a contrast of 0.07 which is only slightly above the threshold contrast of 0.05 and the seeing task is very difficult. An empirical equation is developed for evaluating glare and for an example cited a single glare car would reduce visibility by 60 percent. The decrease in visibility is proportioned to the candle power of the opposing glare light. Speed for driving must be greatly decreased to bring the visibility range against the glare within safe limits.

Thus the range between the luminosity of pedestrians and roads and the excess glare is insufficient for good control of vision. Another useful reference (British) is Stiles and Dunbar (86).

An automobkle headlight is an extended rather than a point source and the inverse square law does not apply except at considerable distances. Lens and reflector design scatter considerable light in directions other than straight ahead. Rarely are lights aligned to the best position. These relations may account for our finding of more light at the driver's eyes as the approaching car comes closer. Unless the distribution of light is known, one cannot compute effects of glare on the eye. Scattered light from a dirty windshield covers more of the retina and decreases seeing proportionally more than does limited direct light. An improved lens design has been announced in the Netherlands to lessen glare (27).

Protection from glare becomes a problem of keeping the unwanted light from the driver's eyes and reducing its spread within the eye. Proper correction for after-dark driving with spectacles lessens glare by focusing the glare source sharply on the retina. Screening must be limited to the dazzling light, as it has been shown that the illumination on the road is scarcely adequate for vision and the eye must obtain an unimpeded view of the highway. This requirement eliminates colored spectacles and windshields. Lauer (5) has suggested placing a strip of purple plastic on the windshield for glare protection to one side of the normal line of sight. Covering the upper-left quadrants of night-driving glasses with a pure-red filter takes advantage of the fact that red light does not change the effective level of dark adaptation to any noticeable extent. Rotating the head counterclockwise very slightly puts the filter between the headlights and eyes without otherwise restricting vision. Such mechanical devices are unacceptable to many drivers.

SPECIAL CONDITIONS OF NIGHT DRIVING VISION

Traffic lights are usually bright enough to be identified. Red can usually be recognized as far away as it can be seen. Blue-green may be seen first, at long distance, by its brightness and later by its color. The visibility of warning signs depends on their size, reflectivity, and illumination. Reflector signs depend on the amount and on the angles of the illuminating and reflected beam. Signs need to be placed farther from the obstacles for night vision, in terms of time to see them and likely speed of driving, but no further than necessary, otherwise the lessened illumination would negate the gain.

Atmospheric conditions, extraneous light, and glare may greatly impair night vision and make difficult any visibility studies on actual driving conditions. Rapidly moving objects are less well seen at night than slower moving ones. Stereoscopic vision is poor and there are fewer clues for vision, such as perspective, parallax, and shadows. Chapanis (23) believes that mental and perceptual factors are more important than dark adaptation, because the seeing situation is complex. Distracting factors are more serious in night driving. Some people with good dark-adapting ability have difficulty seeing at night from lack of training, motivation, or psychoneurosis. Form dicrimination is judged more important for night vision than dark adaptation.

According to Kruithof (50) blurring is of little importance in reading X-ray pictures, and sharp line separation is not necessary in photometry. Perhaps this is why some objects are seen better at night than their contrast would warrant.

Roper and Scott (79) have emphasized the role that silhouette plays in seeing at night. A large mass may be seen before a red taillight is seen and Hoppe (45) has determined size effects on the visibility of vehicles both on the road and in the laboratory. The limitation of the oncoming light to specularly reflecting streaks on a wet night largely accounts for the difficulty of seeing. The nonspecular reflection is lacking, and there is no backlighting for silhouette seeing. Traffic on a road may reduce the reflection constant by 8 to 32 percent (15).

Near objects (under 260 ft.) may be brighter than their backgrounds, while far objects may be darker and seen as masses in silhouette. Tall objects may be seen and distances estimated better with one kind of light than another according to de Boer and Vermeulen (27).

Training has improved night seeing for members of the armed services, and a civilian educational program might lessen night-driving accidents appreciably.

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