Experimental Studies of Night Vision as a Function of Age and Changes in Illumination

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● NIGHT VISION depends upon a pattern of variables all of which interact to produce an extremely complex pattern of visual conditions of the utmost importance to vehicle operators. This in turn means that highway engineers, and vehicle designers should consider the facts of night vision in order to design highways and vehicles in such a way as to enhance the night vision function.

For instance, it is well known that color, placement of light sources, spacing of luminaries, radiation surfaces of light sources, duration, intensity, and frequency of illumination changes are all important. Thus, below certain levels of illumination sodium light does not appear to be superior to mercury or incandescent light; above certain levels, however, sodium light has been shown to be superior to either mercury or incandescent light as measured by its influence on visual efficiency (9, 10, 11). Further experimentation has shown that glare from sodium light produces less deleterious effect than glare from tungsten light sources (28). Acuity and depth perception have been found to be unfavorably influenced by some color bands, especially when green or bluish glass is combined with pink ophthalmic lenses to form a complex filter. Visual acuity may be reduced as much as 20/60 by such a combination (38). Equally important is the night vision recovery time, that is, the rate at which the sensitive cells of the eye adapt to decreasing illumination. This has been shown to be a function of several variables such as the time and duration of pre-exposure, and color.

However, night vision efficiency varies among persons of the same age, among persons of different ages, and it also varies with the physiological state of the viewer. Low blood sugar levels, oxygen deprivation, CO poisoning, and dietary deficiencies, all tend to reduce the final level of night vision and the time required to achieve it (31, 32, 33, 34, 17).

Therefore, night vision or dark adaptation is a function of the nature of the visual stimulus and the physiological states of the viewer. This is important to know because of the consequences associated with either an increase or decrease in the level of efficiency and because of the necessary control and management of this function.

To illustrate, in studies of highway accidents it has been shown that when probability of accident exposure has been held constant that night-time accident fatalities are three times greater than day-time fatalities (1, 49, 41). That this is not circumstantial is suggested by several studies. One study (47) was controlled and carried out in Kansas City, Missouri. The evidence from these several investigations is the same, i.e., when street and road illumination is improved, night-time accidents are reduced (4, 39, 46).

It seems reasonable to assume that as the control of environmental conditions, visual stimuli, and physiological states of the viewer increases, that further improvements in night vision should result, and therefore a measurable reduction in type, frequency, and severity of accidents.

Efficient, scientific control of the variables of which night vision is a function depends upon reliable knowledge of (a) the relevant variables, (b) their magnitude, (c) how they interact, and, (d) how they are distributed in the population.

THE NIGHT VISION OR DARK ADAPTATION PHENOMENON

The night vision or dark adaptation phenomenon is that process which allows the viewer to take maximum advantage of decreasing amounts of light. It is a remarkably stable function, although it becomes progressively less efficient as age increases. It depends upon two types of cells (a) cone cells which are in the minority, and function best under relatively high levels of illumination, and (b) rod cells that function best under low levels of illumination. However, rod cells never acquire the same proficiency as cone cells do, being particularly inefficient in the perception of form and color. The rod cells take over the function of the cone cells when the latter are no longer efficient under low levels of illumination.

When the eye is deprived of light the cone cells adapt to this loss in about 5 to 10 minutes depending upon the degree of pre-exposure to light. Then the rod cells assume the light sensing function of the cone cells and adapt to very low levels of illumination in about 30 to 50 minutes. Any further change beyond this time is negligible, although it is of great theoretical interest.

However, it is seldom that anyone is required to function for any length of time at very low levels of illumination, but in instances when this is necessary, the greater the degree of night vision efficiency, the better. Mostly persons are required to function at a point somewhere between high and low levels of illumination that is not constant but decreases and increases incessantly. Thus, the level of adaptation must also change to accommodate visual efficiency to the ever changing level of illumination. When illumination is high, the rate of adaptation to moderate change is rapid, but when illumination is successively reduced, the rate of change slows down, and equal degrees of adaptation require more and more time. Therefore, the most proficient viewer is the one who can adapt to the most efficient level in the shortest possible time.

Since drivers function most of the time at intermediate illumination levels, they cannot depend upon their ultimate night vision efficiency because they do not reach it. Under these conditions the rate of adaptation becomes more important than final level when tasks must be carried out under intermediate amounts of illumination, especially when continuous momentary adjustment is necessary. This mesopic or middle range, just about at the point where the cone cells have ceased to function, and before the rod cells have acquired adequate efficiency, therefore becomes extremely important in the study of night vision.

It has been possible to analyze this phenomenon in considerable detail. Consequently, a number of important observations have been made that have direct bearing upon both the theoretical and practical problems pertaining to the management of night-vision efficiency. Hammond and Lee (18) became interested in the relationship that one part of the dark adaptation process might have to another part. They found that the rate of adaptation of the cone cells to lowered illumination was not correlated with the final level of night-vision proficiency. But they found that the level of night-vision efficienty after ten minutes in the dark was correlated 0.76 with the rate of adaptation to the dark. They were able to show that the mean log I of time between 10 and 40 minutes was correlated 0.84 with the final level of adaptation, a relatively high degree of relationship. With their 22 young adult subjects they also demonstrated that the time required to reach a visual efficiency level of 4 uul was correlated 0.90 with the rate at which the adaptation was taking place. This is an extremely high relationship. Thus, some but not all phases of the adaptation process are associated.

However, Hammond and Lee did not relate their discoveries to the age of their subjects, and they did not thoroughly investigate the cone cell adaptation process.

Since the process of adaptation to night vision is so stable, and in itself important, it is often used to study the effect of certain variables upon perception or upon the process of seeing. Some of the more important variables known to have a profound effect upon the degree of night vision, and the rate at which it is attained will be discussed herewith. However, several recent unpublished studies will be reviewed independently in a separate section of the paper.

INFLUENCE OF PRE-EXPOSURE ON NIGHT VISION

It has been experimentally demonstrated that the time required to adapt to low levels of illumination is a function of the degree of exposure to different levels of illumination (55). Night vision is considerably less efficient after the eye has been exposed to high levels of illumination, and the reduced efficiency persists for several hours. The practical importance of this point can be demonstrated by the fact that after hours of driving in bright sunlight or after hours spent at the beach in bright sunlight, visual efficiency is reduced (12, 34). If the persons involved were to drive during twilight and early evening, they would do so with less night vision proficiency than others who had not been exposed to bright light for several hours.

INFLUENCE OF LIGHT-WAVE FREQUENCY ON NIGHT VISION

There is evidence that the rate of attaining night vision efficiency is a function of light-wave frequency or color. Wolf (53) has shown that ultra-violet light even for relatively short periods of time results in delaying the rate of adaptation to low levels of illumination. Hecht and Hsia (25) demonstrated that when red and white light were equated for photopic vision and then used to study dark adaptation that adaptation to night vision following pre-exposure to red light was significantly faster than adaptation following pre-exposure to white light. When violet light rather than white light is used as a test stimulus the separation between the cone cell adaptation and the rod cell adaptation to low levels of illumination increases. This was demonstrated by Hecht (20).

INFLUENCE OF DIFFERENT LEVELS OF ILLUMINATION ON VISUAL ACUITY

Acuity, or the capacity of the eye to resolve and discriminate objects decreases as illumination decreases. For instance, Hecht and Mintz reported ". . . . . the visual angle occupied by the thickness of the line when it is just resolved varies from about 10 minutes at the lowest illumination to 0. 50 seconds at the highest illumination, a range of 1, 200 to 1. " (23) Obviously, the capacity to discriminate objects is an important one and every precaution must be taken to maintain this function at the highest possible level.

INFLUENCE OF CHANGES OF ILLUMINATION ON DEPTH PERCEPTION

Depth perception has been shown to vary with changes in degree of illumination. McFarland and Wolf (37) have shown that when illumination was reduced by 30 percent with a filter that stereopsis was reduced from 12. 5 to 37. 5 percent in the test sample. The average reduction was found to be about 25 percent. Serious reductions in depth perception should be avoided because the greater the accuracy with which objects can be located in space, the greater the latitude of control the viewer has over his choice of actions. In some instances failure to perceive allows the operator of a vehicle to enter a fatally dangerous traffic condition from which he cannot extricate himself. Depth perception, important in itself, becomes even more critical when the viewer is traveling at high speeds.

Small but significant differences between accident-free drivers and accident repeaters have been found. The accident-free group was found to be superior in visual acuity, lateral ocular balance, and depth perception. (45)

INFLUENCE OF GLARE ON NIGHT VISION PROFICIENCY

When the field of vision contains a source of light much brighter than the surrounding area, objects reflecting less light become impossible or nearly impossible to see. And when glare is eliminated the rate at which the retina can recover maximum sensitivity is dependent upon the brightness of the exposure, the duration of the exposure, and the area of the retina most stimulated by the glare. Apparently older persons are more susceptible to the glare effect than younger persons (2, 27). In one study it was found that females took longer to recover from glare than males (51). Simonson, Blankstein and Carey (48) found that in three experienced subjects cone cell recovery was faster after exposure to a light source, the spectral range of which had been reduced at both ends, that is, the red and violet ends, as compared with exposure to the usual frosted lamps. The shape of the dark adaptation curve did not seem to be influenced, but the rate of recovery increased after exposure to the experimental light. The comparative effect was not a function of pre-adaptation brightness, daily variability, or individual differences. Thus, the glare effect also seems to vary with the area of the color band used in pre-exposure.

The effect of age on the ability to see under night driving conditions was determined by the use of a Night-Sight Meter. The repeat reliability of the apparatus was high, and the improvement in scores as a result of practice and dark adaptation was not serious, thus, these experimental variables did not influence the validity of the data. The test was administered to 474 men and 806 women (age range 15 to 89 years) of which one-fifth of the persons were 50 years of age or older.

Scores were obtained from two conditions: (a) the amount of illumination necessary to make the test target just visible, and (b) the change of illumination necessary to make the target visible in the presence of glare. The intensity of the glare source was comparable to the intensity of approaching headlights at 100 to 150 ft, and the angle between the glare source and the test target was similar to an angle between an approaching car at 150 ft and a pedestrian walking on the edge of a 20-ft pavement in front of the driver. Both glare and night vision scores became poorer as age increased. The trend was slight but consistent up to 50 years of age, quite pronounced from 50 to 70, and very pronounced after 70. Without glare interference the amount of light needed to identify the target was much less, so that the increase in illumination necessary to make the test target just visible was four times as great when glare was present as when it was absent.

On both the glare and night vision test the persons who had abnormal visual acuity (one or both eyes at 14 in. or 20 ft) had poorer than average scores on all age levels. About 22 percent of the persons tested had abnormal visual acuity. There was no significant difference in scores made by men and women at all age levels on both the night vision and the glare test. Table 1 shows the increases in illumination necessary to see a standard, briefly viewed, moving stimulus with increasing age.

TABLE 1

CHANGE IN ILLUMINATION NECESSARY TO SEE A STANDARD, BRIEFLY VIEWED, MOVING STIMULUS WITH INCREASING AGE (Adapted from ref. 2)

	Relative Illumination Necessary		
Age Group	(x) in Presence of Glare Source	(y) Without Glare Source	x - y
15 - 19	1.00	1.00	0.00
20 - 24	1.15	1.10	0.05
25 - 29	1.28	1.17	0.11
30 - 34	1.36	1.20	0.16
35 - 39	1.54	1.27	0.27
40 - 44	1.78	1.33	0.45
45 - 49	2.24	1.48	0.76
50 - 54	2.83	1.94	0.89
55 - 59	3.42	2.32	1.10
60 - 64	5.18	2.92	2.26
65 - 69	10.25	4.47	9.78
70 and up	17.12	10.13	6.99

N. B. No pupillary control.

INFLUENCE OF LIGHT "SHOCK" ON NIGHT VISION

Light "shock" occurs when a bright light is presented briefly to the retina. In every day life this is a common event, especially prevalent in night driving. Unless the tachistoscopic presentation is repeated frequently the recovery from light shock is "rapid". Repeated presentations lead to cumulative effects, and the greater the frequency, the greater the delay in recovering night vision proficiency. In one experiment (54) a two-degree square field was presented ten degrees below center. After 30 minutes of adaptation to the dark, a bright light (370 millilamberts) was presented for 0.04 seconds. Night vision was quickly reduced, although not completely, and the time required to recover a two-log unit loss was about 40 seconds.

Generally, the vehicle operator will be repeatedly stimulated with flashes of bright light, a special instance of the condition of glare. The consequence is largely the same; a reduction of visual efficiency accompanied by the necessity of continuous adjustment to an unstable level of illumination.

INFLUENCE OF AGE ON ADAPTATION TO NIGHT VISION

Pinson (42) examined the night vision or dark adaptation process of 204 subjects between 20 and 50 years of age and found that the major part of the adaptation curve, the rod cell curve of adaptation to reduced light, was correlated with age. And although he found that subjects age 40 and above had 30 to 60 percent reduction in night vision efficiency he stated, "The trend toward a decline in average dark adaptation proficiency with age is of minor significance in comparison with individual variations in the dark adaptation proficiency." He also reported that age and the point where the rod cell curve of adaptation began, the mesopic range, was "...the only characteristic of the curve of night vision efficiency which was independent of age."

Hecht and Mandelbaum (22) and Robertson and Yudkin (43) have reported marked differences in night vision efficiency with age. Robertson and Yudkin studied 758 English shoe factory workers, an unusually large sample with ages 14 through 74 years. Birren (7) found that pupil size reduced significantly as age increased under both light and dark conditions, thus limiting the amount of light that could reach the retina of the eye. Birren, Bick, and Fox (5) reported significant changes with age of the dark-adapted eye in a sample which ranged from 18 through 83 years. Birren and Shock (6) found no correlation between rate of adaptation to night vision and age, but a significant decrease on the final level of proficiency with older subjects.

McFarland and Fisher (35) conducted an extensive study of alterations in dark adaptation as a function of age. In a preliminary study 200 males between 20 and 60 years of age were tested on the Hecht-Schlaer adaptometer, with pupil size controlled. The mean levels of final adaptation for five age groups showed a regular increase with age, and the intensity of illumination required by the age group 40 to 47 was about 150 percent greater than that required by the youngest group. In the second part of the experiment, additional subjects were tested, particularly those under 24 years of age, and those above 47. Final adaptation levels were calculated for all subjects, and correlated with age. The coefficient obtained was 0.895, and from the data, it was estimated that for each increase of 13 years in age, the intensity of illumination must be doubled for a light to be just seen. The rate of dark adaptation was approached by a graphic solution based on the "decay" characteristics of the dark adaptation curve. Rate was not found to bear a linear relationship to age. The limitation in the ability to see at night is quite marked in older subjects, and the experimental findings may help to explain the difficulties persons over 55 or 60 years of age have in driving or flying at night. The changes in dark adaptation are believed to be related to certain basic physiologic functions in the nerve cells of the retina and brain.

INFLUENCE OF CHANGES IN PHYSIOLOGICAL STATES ON VISUAL SENSITIVITY

To emphasize the fact of the interaction between the environment and human physiological processes, certain variables now known to have marked influence on the dark adaptation process and night vision will be reviewed (31, 32, 33, 34, 17).

The alteration of certain visual functions by anoxia and other physiological stresses has yielded results of considerable theoretical interest and practical significance. The study of vision under such conditions is important, not only because of the role of this sense in driving or flying, but also because certain visual functions are believed to reflect changes in the central nervous system, of which the retina of the eye is essentially a part.

The series of experiments to be described are concerned with four main problems: (a) the effects of oxygen deprivation on differential brightness sensitivity; (b) the effects of insulin hypoglycemia on differential brightness sensitivity; (c) the role of high blood sugar levels in counteracting the effects of oxygen lack; and (d) carbon-monoxide anoxia at sea level and at simulated high altitudes. An additional area took dietary deficiencies into account.

The Effects of Oxygen Deprivation on Differential Brightness Sensitivity (31)

Earlier experiments on dark adaptation have revealed that one's ability to see dim objects against a very dark background is markedly impaired by oxygen lack. In practical situations, however, it is rarely necessary to distinguish objects against a totally dark background.

In this study, measurements were made of the sensitivity of the eye to foveal stimuli presented against backgrounds which varied in intensity over a range of about 1:100, 000. It was found that anoxia affects visual sensitivity to the greatest extent when the background is most dimly illuminated. The effect becomes less marked as the intensity of the background increases. At very high light intensities, as in sunlight, oxygen lack produces practically no change in visual sensitivity.

Effects of Insulin Hypoglycemia on Differential Brightness Sensitivity. (34)

The concentration of blood sugar is intimately related to the functioning of the central nervous system. This is true because glucose is practically the only substance which can be utilized by the central nervous system as a fuel, or metabolite. If the supply is deficient, the oxidative processes are slowed, and the effect should be equivalent to that of a reduced sypply of oxygen. The retina behaves very much like the central nervous system in regard to its metabolism.

In a normal subject under ordinary conditions, the blood sugar level did not become sufficiently low to impair visual sensitivity. Such impairment occurred only when the blood sugar concentration fell below about 65 to 70 mg. per 100 cc. However, these findings are important in explaining the results of the following experiments which are more directly applicable to practical situations.

In the present experiments, differential visual sensitivity underwent the same changes when the blood sugar was reduced by intravenous injection of insulin as when the oxygen supply was reduced. The differential threshold was affected most acutely when the background illumination was dim. Furthermore, it was found that inhalation of 100 percent oxygen counteracted a large portion of the adverse effect caused by hypoglycemia.

Role of High Blood Sugar Levels in Counteracting the Effects of Anoxia. (33)

The results of the preceding experiments suggested the possibility that high blood sugar levels might have an opposite effect. Studies were made, therefore, of the differential sensitivity during oxygen lack equivalent to altitudes of 12, 000 to 16, 000 ft, before and after the administration of 50 gm of glucose. A dim background was again employed.

It was found that elevation of the blood sugar level from a fasting value of about 100 mg per 100 cc to a peak value of about 180 mg counteracted about one-third to one-half of the impairment caused by anoxia. The effect of an oxygen tension corresponding to 16, 000 ft altitude, for example, was reduced to that ordinarily caused by 10, 000 to 12, 000 ft altitude. Visual sensitivity varied in a manner parallel with the blood sugar level. Similar results were obtained whether the sugar was given during oxygen deprivation or whether it was given before oxygen deprivation in order to prevent its effect. During control experiments, on the other hand, a saccharin solution had no effect. It was found also that high blood sugar levels improved visual sensitivity only when this function had first been impaired by anoxia or hypoglycemia, and then only to its original value.

Carbon-Monoxide Anoxia at Sea Level and Simulated High Altitudes. (32, 17)

Carbon monoxide may be absorbed from at least two sources: engine exhaust gas and tobacco smoke. When carbon monoxide combines with hemoglobin, the oxygen-carrying capacity of the blood is reduced. Furthermore, carbon monoxide displaces the oxygen dissociation curve to the left, thus inhibiting the release to the tissues of even this decreased amount of oxygen. As a result, there is a marked lowering of the tissue oxygen tension. This accentuates the anoxia caused by exposure to high altitude.

Theoretical considerations have led to the conclusion that the venous (or even tissue) oxygen tension, which is associated with the loss of a given percentage of the oxygen capacity of the blood due to saturation with carbon monoxide, is the same as that caused by a similar decrease in arterial oxygen saturation at high altitudes. On this basis, five percent saturation with carbon monoxide would be expected to have an effect equal to that of an altitude of about 8,000 to 10,000 ft, on those functions which depend on the tissue oxygen tension.

Earlier attempts to determine the least amount of carbon monoxide capable of producing impairment of psychological functions have yielded no clear results. Even with 30 to 35 percent saturation, causing numerous subjective complaints such as headaches, there was no clearly demonstrable impairment in psychological tests. This was probably due to the fact that the tests employed were not sufficiently sensitive and that the subject could mask a considerable degree of impairment during such tests by exerting additional effort. In the measurement of visual sensitivity, on the other hand, compensation is not a factor. The subject merely reports whether or not he sees a flash of light and is not aware of the intensity required.

A series of experiments was carried out to determine the effect of carbon monoxide on visual thresholds, both in normal air and in combination with varying degrees of oxygen deprivation. The results were entirely consistent with the theoretical expectations. It was found, for example, that five percent saturation with carbon monoxide depresses visual sensitivity to as great an extent as anoxia at 8,000 to 10,000 ft altitude. Fifteen percent saturation caused an impairment corresponding to that at about 15,000 to 19,000 ft. At various simulated altitudes, the addition of carbon monoxide, causing a given percentage of saturation, produced an effect equal to that at an altitude sufficient to produce an additional loss of arterial oxygen saturation of the same amount.

The test proved to be so sensitive that even the effects of the small quantities of carbon monoxide absorbed from cigarette smoke were clearly demonstrable. Inhalation of the smoke from a single cigarette caused a carbon monoxide saturation of almost two percent. After inhaling the smoke of three cigarettes, the saturation of the blood with carbon monoxide was approximately four percent and the effect on visual sensitivity was equal to that at an altitude of about 7,500 ft. The loss of arterial oxygen saturation at this altitude is about four percent. The absorption of a similar amount of carbon monoxide at 7,500 ft altitude causes a combined loss of sensitivity equal to that at 10,000 to 11,000 ft. (32)

The inhalation of 100 percent oxygen was found not only to accelerate the elimination of carbon monoxide but also to produce an improvement in visual thresholds at any given point after inhalation. The improvement was equivalent to a decrease of about 5 to 7 percent carboxyhemoglobin when breathing oxygen as compared to room air. If, instead of oxygen, the subject breathed atmospheric air throughout the recovery period, the visual thresholds failed to recover as rapidly as the percentage of carboxyhemoglobin declined. (17)

These studies indicate that carbon monoxide may be harmful in much smaller amounts than previously supposed. The importance of guarding against the entry of exhaust gases into an automobile or airplane and of adequate removal of gases liberated by gunfire is therefore intensified. The importance of refraining from excessive inhalation of tobacco smoke and the value of the use of oxygen in flight is obvious. Theoretical considerations had led to these same conclusions previously, but these studies represent an objective demonstration of the dangerous effects of small quantities of carbon monoxide, especially if combined with anoxia or low blood sugar.

Effect of Vitamin A Deficiency on the Dark Adaptation Process or on Night Vision Efficiency.

Alcoholism is often associated with cirrhosis of the liver which in turn is frequently characterized by Vitamin A deficiency. Since Vitamin A deficiencies supposedly increase the visual threshold in dark adaptation and night vision, it would be expected that acute alcoholics would show a disturbance of night vision. Haig, Hecht, and Patek (16) studied the dark adaptation process of 14 alcoholics suffering from cirrhosis of the liver, and 13 of them plainly showed evidence for disturbances in dark adaptation or night vision. After 105 to 127 days of Vitamin A treatment both the cone cell and rod cell sensitivity had increased significantly, that is, dark adaptation and night vision proficiency had increased. The authors stated:

"The most striking aspect of these changes is the fidelity with which the cone thresholds vary with the rod thresholds. Since the rod thresholds apparently are changing in response to alterations in Vitamin A concentration, the concomitant cone threshold variations indicate a similar dependence upon the presence of the Vitamin."

An important observation was that those persons suffering from cirrhosis of the liver and Vitamin A deficiency simultaneously also showed a delay in cone cell adaptation, and a delay in the initiation of rod cell adaptation. However, Hecht and Mandelbaum (21) showed that this delay is not present in normal subjects deprived of Vitamin A but not suffering from cirrhosis of the liver. This may mean that there is a connection between cirrhosis of the liver and blood sugar deficiency which is known to independently influence night vision adversely. Whether this involves a delay in the rate of cone cell adaptation is not know. It does involve an increase of sensitivity threshold.

One year later Hecht and Mandelbaum (22) reported a study of the dark adaptation or night vision process of 110 university subjects. They stated that age increases the cone sensitivity threshold, that is, that older subjects are less sensitive, but that rod threshold is only slightly influenced by age, and that rod-cone transition time is not affected at all. Of the 110 subjects, 4 young men were deprived of Vitamin A. Following this experimental condition, both cone and rod vision were decreased in sensitivity, and this reduction of sensitivity continued throughout the two weeks of Vitamin A deprivation. Although the restoration of a normal diet was followed by an initial improvement in dark adaptation or night vision proficiency, nearly two months were required before a return to complete normality was achieved.

Wald and Steven (52) studied one subject, age 22, who was first saturated with a high Vitamin A diet for 18 days. During this time some improvement in night vision was apparent. Following this phase, the subject was deprived of Vitamin A. Then, the sensitivity of night vision decreased. By the 34th day of Vitamin A deprivation, the cone sensitivity had decreased by a factor of nearly 4, and the rod sensitivity by a factor of 9. The authors state that the night blindness of the subject was completely reversed by a single administration of carotene. Wald and Steven suggest that dietary deficiencies other than Vitamin A could also influence night vision proficiency.

Hecht and Mandelbaum (24) reported another study of 17 young men who were subjected to a deficient diet. Fourteen of the 17 subjects showed an immediate reduction in both cone and rod cell sensitivity. Partial recovery occurred immediately after a single dose of Vitamin A, but the recovery was never complete and was always temporary until normal diet was restored. It was interesting to discover that treatment by vitamins other than Vitamin A gave negative results.

McFarland, Graybiel, et al. (30) were able to show that night vision sensitivity was reduced in subjects with Vitamin A deficiency. After large doses of Vitamin A, the general trend was toward recovery of normal dark adaptation thresholds.

INFLUENCE OF COLORED FILTERS ON VISUAL PROFICIENCY

Between 1950 and 1955 more than 5 million automobiles have been equipped with heat-absorbing tinted windshield glass. By eliminating more than 50 percent of the radiant solar energy in the infrared part of the spectrum the comfort of occupants of automobiles may be somewhat increased, but at the same time the loss of transmissiveness reduces visibility, thus creating a potential safety hazard.

The light transmission of certain tinted windshields is reduced by approximately 30 percent, the limit permissible according to the American Standard Safety Code (3). While a 30 percent loss in light transmission does not influence visibility adversely at photopic luminance levels, the reduction is a matter of more serious consequences at mesopic and scoptopic luminance levels. In an attempt to clarify this problem the distance at which low contrast targets can be detected was determined in practical situations by Heath and Finch (19), using as targets such objects as road signs, posts, boxes, dirt piles, of varying reflectance. Roper (44) exhibited against the glare of oncoming headlights 15-inch square panels of low reflectance. Doane and

Rassweiler[1] (13) used targets simulating pedestrians distributed along both sides of the road, having a reflectance of 7 percent on one side, and 3 to 3.5 percent on the other. Since a number of not easily controllable factors are involved in tests of this type, differences in results are readily to be expected. Roper found 6 percent, Doane and Rassweiler, 3 percent, but Heath and Finch as much as 22 percent loss in visibility distance. Despite these differences the net conclusion of the investigators is that the losses in night visibility are not serious and are compensated for by the beneficial effects of glare reduction and heat absorption during daytime driving.

Clinical tests conducted by Miles (38) have shown that all tinted filters—light yellow, pink, and greenish-blue windshield glass—reduce visual acuity at mesopic luminance levels, and that tinted windshield glass combined with pink ophthalmic lenses is particularly disadvantageous, reducing visual acuity to 20/60. At luminance levels involved in night driving, the resolving power of the eyes is greatly reduced. Thus, a pair of targets which appear distinctly separate at 100 ft in unrestricted vision when seen through a clear windshield must be brought to a distance of 25 ft for distinction when they are viewed through a tinted windshield.

In 1954 in laboratory tests Blackwell (8) found a 23 percent loss in detection distance when targets were viewed through tinted windshield glass. As distance for detection without tinted filters became smaller, owing to a reduction of target size or luminance level, the percentage loss in detection distance increased rapidly with the tinted filter. From these findings Blackwell concluded that the loss in visual detection resulting from the use of filters at low luminance levels is so great that such filters are scarcely to be recommended unless drivers reduce vehicular speed accordingly. However, vehicle operators are not usually aware of the degree of reduction of visibility induced by tinted windshields.

In 1955 Haber (15) analyzed the effect of tinted windshield glass upon visibility theoretically. According to his findings visibility distance is reduced 9 to 15 percent at distances greater than 200 ft when targets are viewed through a tinted windshield. If, however, the contrast between target and background is low, so that detection through a clear windshield is possible only at a short distance, the percentage loss in visibility may be as high as 35 to 45 percent with a tinted windshield.

In 1956 McFarland and Wolf (37) conducted a series of related experiments designed to test in the laboratory the influence of tinted windshield glass upon, (a) dark adaptation, (b) recovery from light shock, (c) visual acuity, (d) depth perception, and (e) glare. And McFarland, Domey, Warren, and Ward conducted an experimental study of the influence of age and tinted windshield glass on dark adaptation (36).

Tinted windshields consist of a bluish-green plastic filter material laminated between two sheets of safety glass. The thickness of each glass pane is ⅛ in. The lower three-quarters of a windshield are uniform in density but the upper quarter represents a darker band increasing in density toward the top edge. Since only the honogeneous part is in the path of vision in looking at objects at eye level or below, the present studies were made only with glass filters cut from the midsection of the homogeneous part of the windshield.

The spectral transmission curves for two kinds of windshield glass were first determined. Both types transmit similar spectral ranges. The total transmission of A is greater than that of B. The transmission maximum for A is found near 500 millimicrons, for B near 480 millimicrons. B has a relatively lower transmission at both ends of the spectrum than A. By holding an A and a B filter side by side, the higher density and more bluish color of B can easily be noticed. Only filters of type A windshield glass were used in the experiments to be described here. Transmission measurements of

[1] The unusually low value obtained by Doane and Rassweiler may be attributed to several conditions of the experiment. (1) data from several subjects were eliminated, (2) the sample of 6 subjects was small, (3) subjects were familiar with the track, (4) age was not controlled, (5) subjects repeated the test many times, (6) the several targets were fixed and not randomized from trial to trial, and (7) apparently any possible learning effects were not accounted for in the data.

various samples of A-glass with a Macbeth illuminometer yielded values between 65 and 69 percent.

Since tinted windshield glass can by no means be regarded as a "neutral" filter it seemed desirable to make comparisons with other filters having different spectral characteristics but approximately the same amount of transmission. Such filters are Cruxite B which has a brownish tint, and a transmission of 72 percent, and Noviol C which is deep yellow and has a visual transmission factor comparable to that of the other filters, if two sheets of filter glass are combined.

In the McFarland, Domey, Warren, and Ward studies, the dark adaptation process of 240 subjects ranging from 16 to 89 years of age was measured. (29) Each subject was seated and then his left eye was covered with a patch, and the retina of the right eye was bleached for three minutes by exposure to a standard light source of 1, 600 ml. The fixation point was 7 deg left of center and violet light was used for testing. Immediately upon termination of this process the first response to the adaptometer stimulus test light was obtained. After the first reading, taken within the first 40 sec after exposure to the bleaching light, beginning with the first observation, one observation was taken every min for 10 min, then every two min for the next 6 min, every three min for the following 24 min, and finally every min for the last 10 min, 50 min in all.

At the 41st min the first glass filter obtained from an ordinary windshield was inserted between the viewer and the test light. The transmission factor of this glass was about 90 percent. On the 46th min a second filter cut from the middle section of a popular tinted (green) windshield was substituted for the clear glass filter. The transmission factor of this glass was about 73 percent. Therefore, the first filter was not used until the 41st min of adaptation, and the second was not used until the 46th min of adaptation. Five observations were made with clear glass, and five observations were made with tinted glass. All observations were taken without an artificial pupil and when vision was uncorrected.

In addition to the dark adaptation data, a standard eye examination was administered to 178 of the 240 subjects. More than half of the subjects in each age group was examined, thus assuring a fair sample of the efficiency of vision of persons participating in this experiment. Because the curves for 13 subjects were highly distorted, they were omitted from the statistical analysis.

The mathematical treatment was as follows:

$$y = a\,e^{-bt} + c\ ,$$

was fitted to the cone curve, and another of the same form was fitted to the rod curve. The parameters for the cone curve were called a, b, and c, and for the rod curve a', b', and c', so that c is the asymptote of the rod curve and estimates the ultimate adaptation that should be attained at the end of an indefinitely long time. Also, a was equal to the differences between the first obtained value and c, and b was the drop rate.

The method of residuals (35) was used to fit the curves by least squares. The determination of the "cutting point" between the cone curve and the rod curve was determined by least squares also. That is, the pair of curves for any individual was fitted with, say, the first five points on the cone curve, and the remaining 15 on the rod curve. The sum of the 20 squared discrepancies was computed. Then the first six points were assigned to the cone curve, and the remaining 14 to the rod curve, and the least squares parameters were again determined, and the sum of the 20 squared discrepancies from this second fitting was compared with the earlier sum of 20 squared discrepancies. The pair of curves finally accepted as the "best fit" was the pair showing, among all pairs, the least sum of 20 squared discrepancies of the original data from the fitted curves. The details of the procedure are to be given in a separate publication (24).

Table 2 shows the degree to which Age, a, b, c, and c' were correlated as independent pairs and as a multiple correlation (See page 28).

It can readily be seen that the asymptote of the cone curve, c', was correlated with Age, and that of all the variables, Age proved the most influential.

The influence of tinted glass upon dark adaptation is represented by the terrace-like rises at the ends of the curve. The first rise occurred when the subjects were exposed to ordinary windshield glass used as a filter between the test light source and the viewer.

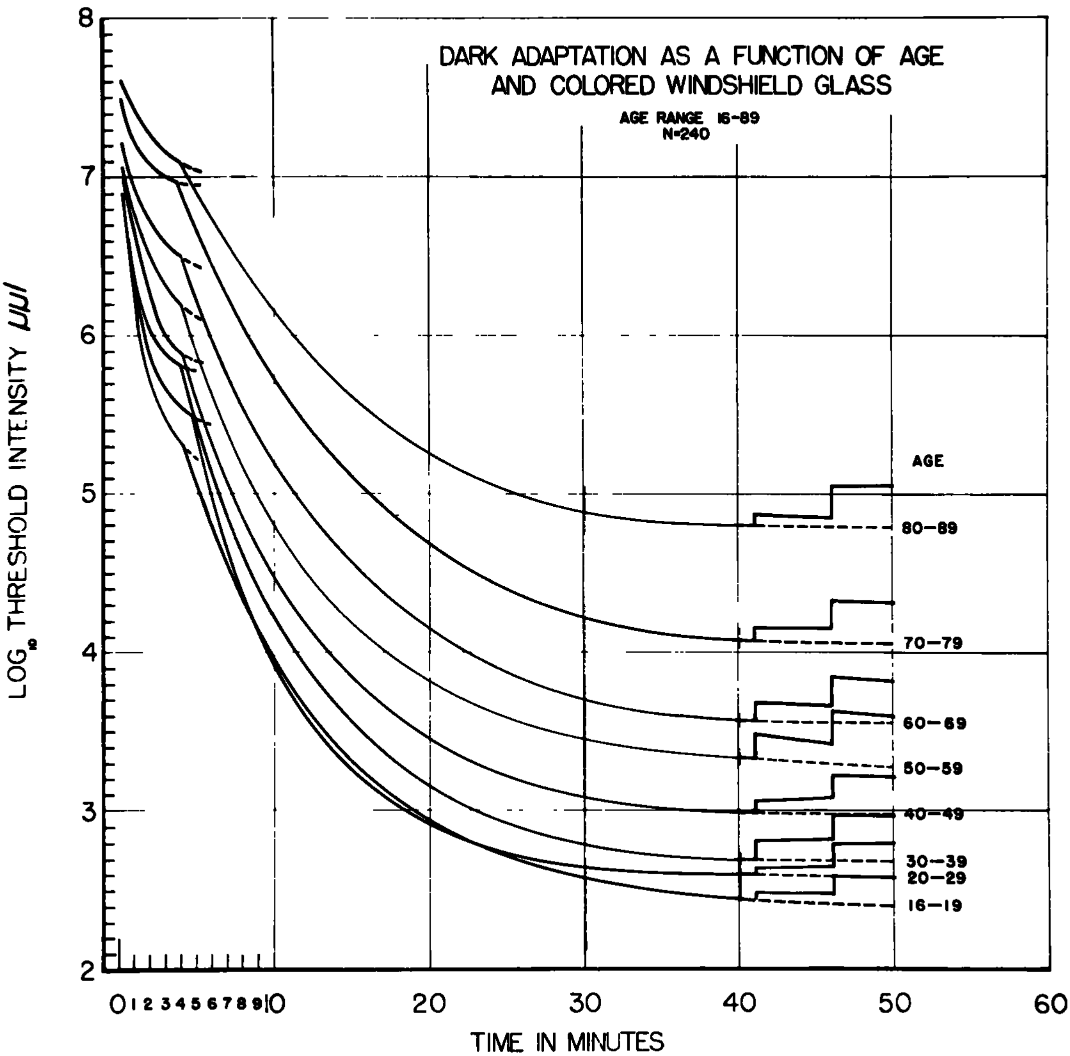

Figure 1.

The second rise occurred when tinted windshield glass was then substituted for clear windshield glass. It can readily be seen that the viewer demanded more light before he could see the test patch in both instances. His demand was greater after the introduction of the tinted glass.

There is a suggestion that the tinted windshield glass appears to influence the dark adaptation level more adversely for the aged than for the younger subjects. Columns D and G-I in Table 3 suggest this relationship.

Study of Figure 1 will show that with tinted windshield glass the final level of dark adaptation for the group aged 50-59 is not much better than the level of adaptation at the 12th min for teen-aged subjects, obviously before they have reached their final level of adaptation. Another way of putting the same thing would be to say that the increase of the 50-59 age group dark adaptation threshold induced by tinted windshield glass functionally equates them on the average with the group of people who fall in the 60-69 age group. Thus, the effect is to increase the functional "night vision" age of this group by about 10 years on the average.

If the 80-89 year old group is studied, tinted windshield glass functionally regressed the visual efficiency of this group back to the level expected at about the 25th min or

TABLE 2

CORRELATION - DARK ADAPTATION, Age, a, b, c, c'.[1]

	Age	a	b	c	c'
Age	1.000	0.475	0.026	0.549	0.752
a		1.000	0.0390	-0.735	-0.299
b			1.000	0.490	0.044
c				1.000	0.402
c'					1.000
M	50.237	1.963	0.662	5.620	3.139
S.D.	22.899	1.352	0.475	1.293	3.139
beta	0.764	0.139	0.030	0.099	----

N—There were 227 subjects.[2]

Multiple R 0.756

Note: All r values underlined are significantly different from zero.

[1] These values were derived by P. J. Rulon, Director, Educational Research Corporation, Cambridge, Massachusetts.

[2] Because of extreme visual pathology, 13 Ss were omitted from the original sample of 240 Ss, hence N equal to 227.

TABLE 3

NIGHT-VISION WITHOUT FILTER AND WITH CLEAR AND TINTED WINDSHIELD GLASS AS A FUNCTION OF AGE

Age	B Log_{10} uul without filter 40th Minute	B (H-G) d	H Log_{10} uul With Clear Windshield Glass Average 41st-45th Minute	D (I-H) d	I Log_{10} uul With Tinted Windshield Glass 46th-50th Minute	F (G-I) d
16-19	2.427	0.019	2.446	0.125	2.571	0.144
20-29	2.602	0.030	2.632	0.146	2.777	0.176
30-39	2.694	0.095	2.789	0.163	2.952	0.258
40-49	3.016	0.027	3.043	0.161	3.204	0.188
50-59	3.346	0.062	3.408	0.192	3.600	0.254
60-69	3.642	0.011	3.653	0.163	3.813	0.174
70-79	4.104	0.038	4.142	0.164	4.306	0.202
80-89	4.806	0.041	4.847	0.183	5.030	0.224

The rise of the differences in Column D suggests that tinted glass decreases the dark adaptation sensitivity of older subjects to a slightly larger extent than it does for younger subjects. The greater the $\log_{10}$ value the less efficient the vision.

before they have reached even their poor final level of adaptation. But this group is visually so much more inefficient than any of the younger groups that any reduction of illumination should be avoided. With tinted windshield glass this group resembles teenagers at about the 5th-6th minute of adaptation, precisely at the cone-rod cell junction, or in the mesopic range, one of the most inefficient points on the dark adaptation curve. The aged must also cope with slower rates of adaptation when even their already inefficient levels of adjustment cannot be stabilized in night driving because of the exposure to intermittent headlight glare. It is precisely when continuous adjustment is necessary that rapid rates of adjustment are most necessary, and slow rates of adjustment most disadvantageous.

In studies of the effect of tinted windshield glass on dark adaptation, recovery from or adaptation to light shock, visual acuity, depth perception, and visibility in the presence of glare, it has been shown that a reduction of visual function occurs with a tinted windshield in proportion to the absorption of radiant energy. When filters of approximately the same density but with different transmission characteristics were used, the reduction in visual efficiency was the same as with tinted windshield glass, indicating that it is rather the loss of luminance than the spectral selectivity which was responsible for reduction in visual function. In visual acuity, stereopsis, and glare tests a balancing of the loss in radiant energy might have been expected on the basis of limited spectral transmission, whereby a reduction of scatter of light and an enhancement of visibility might be achieved. This is not found to be the case. Owing to the bluish-green tint of the windshield glass light scatter might be even greater than with other filters of equal density but higher transmission in the long-wave region of the spectrum. Tests with Noviol and Cruxite do not indicate that the color of the filter materially influences visual performance. Furthermore tests with a stigmatoscope and small spherical corrections do not indicate that chromatic aberration is a decisive factor in influencing the results with the tinted windshield glass.

Glare has to be regarded as an entoptic phenomenon, into which enter such factors as diffuse transmission of light through the iris and sclera; flares, produced by multiple reflections at the different refracting surfaces; specular reflection from the front surface of the retina; halation produced by reflection at the pigment epithelium, choroid and sclera; light reflection through the vitreous from one part of the retina to another; fluorescence of the lens; and scatter by the ocular media (26, 50, 14). Effects of glare seem to be somewhat mitigated by the exclusion of short wave radiation from the glare source. This might be in part a reason for claims that yellow, or amber filters are advantageous in coping with glare.

When a glare source is viewed while the ambient illumination is sufficiently high the ill effects of glare are not experienced in their full extent. The glare effect increases as the contrast between glare source and surround becomes greater. Also the glare effect is lessened with large sources by which a greater retinal area is stimulated, since glare is inversely proportional to the area of the source. For this reason it has been suggested that the size of headlights ought to be increased (38).

Another factor contributing to the annoyance of glare in automobile driving consists in the dispersion of light in the windshield. With an absolutely clear and homogeneous medium between the eyes and a glare source, the image of the glare source is sharp, and flares and halations are reduced. The surface film of small particles on the windshield undoubtedly adds to the unpleasant effects of glare. It would therefore seem desirable to develop and apply adequate means for the elimination of surface film and fogging of windshields.

Since the purpose of tinted windshields is twofold, namely (a) the screening of radiant heat, and (b) glare reduction, the essential question seems to be, whether a tinted windshield is the proper and the only possible solution to this complex problem. It seems questionable whether heat absorption by tinted glass is of any real value as long as dark colors of automobile bodies will absorb far more heat than that which is excluded by the heat-absorbing glass. It also should be remembered that the heat absorption of glass does not depend upon a dark light transmission reducing tint.

In the McFarland, Domey, and Warren experiment, the tinted windshield glass was not the same as in the McFarland and Wolf study. Although the brand was different the transmission factor was about the same.

Many other relationships could be pointed out, but these interpretations will serve to illustrate the effect of the experimental variables and their combination upon night vision or the dark adaptation function.

In not a single instance was it demonstrated that tinted windshield glass improved the visual efficiency of any subject. On the contrary, in every instance the data clearly demonstrated that a reduction of illumination was invariably associated with a reduction of visual efficiency. As the age of the viewer increased this reduction became more and more critical since it was apparent that no subject could afford to experience light loss, the older subjects least of all. And as age increased, the effect of tinted windshield glass became the equivalent of raising the functional "visual age" of the subject or regressing his efficiency far back in time on the curve of adaptation. If such glass is used, a lighter density for the tinted portion should be placed at the sitting eye level of the drivers.

SUMMARY

1. Dark adaptation, recovery from light shock, visual acuity, depth perception and visibility under glare conditions were studied when the targets were seen through tinted windshield glass. The results were then compared with those obtained with filters, or with filters of different absorptive properties.

2. The tinted windshield glass used in these tests is an absorptive filter of light bluish-green tint with a transmission maximum near 500 millimicrons. The percentage transmission of this type of glass is approximately 70 to 73 percent.

3. Thresholds are about 0.15 log unit higher in dark adaptation tests, when tinted windshield glass is used in front of the test light as compared with the condition when no filter was used. The higher threshold corresponds to the loss in test field luminance produced by the filter.

4. After a light shock, recovery time is 1.2 to 1.4 times longer when the test target is shielded by tinted windshield glass than when no filter is in front of the target. The increase in recovery time is proportional to the loss in luminance.

5. Using Landolt rings of small size differences as targets visual acuity is less when a tinted windshield is placed between observer and target than when no filter is used. Besides the lower luminance, prismatic effects produced by two curved, heavy laminated sheets of glass are responsible for reduced visual acuity.

6. Depth perception tests with a Verhoeff stereoptor yield about 25 percent poorer results when a tinted windshield is in the path of vision than when no filter is involved.

7. When thresholds are determined at which targets at fixed angular distances from a glare source become visible, it is found that the ratios of glare luminance/ target luminance are the same, whether glare source and target screen are shielded by tinted windshield glass or are not shielded by an absorptive filter.

8. The results of these tests could not be interpreted as being favorable to the use of tinted windshields, insofar as visual efficiency at low levels of illumination is concerned.

9. Statistical analysis of a large sample ranging from 16 through 89 years of age indicates that age is the best known predictor of the eventual level of dark adaptation.

10. Age, the initial level of adaptation, and the asymptotes of the cone and rod curve are reliably statistically correlated.

11. The initial level of adaptation is negatively correlated with the asymptote of the asymptotes of the cone and rod curve, and the final level of adaptation, or the asymptote of the rod curve.

12. The drop time of the cone curve is positively correlated with the asymptote of the cone curve.

13. The asymptote of the cone curve and the final level of adaptation are reliably correlated.

REFERENCES

1. "Accident Facts." National Safety Council, Chicago, Ill., 1945-1955 editions.

2. "Age and the Ability to See at Night." Res. Rep. No. 43, Traffic Engineering and Safety Dep., American Automobile Assn., Washington, D.C. (1953).

3. "American Standard Safety Code. Z., 26.1-1950." Am. Standards Assn. (1950).

4. Anon. "Road Lighting in the United States." Nature, 139 (3510): 241-242 (1937).

5. Birren, J.E., Bick, M.W., and Fox, C., "Age Change in the Light Threshold of the Dark Adapted Eye." Jour. Gerontol., 3(4): 267-271 (1948).

6. Birren, J.E., and Shock, N.W., "Age Changes in Rate and Level of Visual Dark Adaptation." Applied Physiol., 2(7) : 407-411 (1950).

7. Birren, J.E., Casperson, R.C., and Botinick, J., "Age Changes in Pupil Size." Jour. Gerontol., 5(3) : 216-221 (1950).

8. Blackwell, H.R., "Visual Detection at Low Luminance Through Optical Filters." HRB Bull. 89, p. 43 (1954).

9. Bouma, P. J., "The Definition of Brightness and Apparent Brightness and Their Importance in Road Lighting and Photometry." Philips Technical Rev., 1(5): 142-146 (1936).

10. Bouma, P. J., "Visual Acuity and Speed of Vision in Road Lighting." Philips Technical Rev., 1(7): 215-219 (1936).

11. Bouma, P. J., "Perception of the Roads when Visibility is Low." Philips Technical Rev., 9(5): 149-157 (1947).

12. Clark, B., Johnson, M. L., and Dreher, R. E., "The Effect of Sunlight on Dark Adaptation." Am. Jour. Ophth., 29(7): 829-836 (1946).

13. Doane, H., and Rassweiller, G. M., "Cooperative Road Test of Night Visibility through Heat Absorbing Glass." General Motors Corp. (1955).

14. Fry, G., "Evaluating Disabling Effects of Approaching Automobile Headlights." HRB Bull. 89, p. 38, (1954).

15. Haber, J., Jour. Opt. Soc. Am., 45: 413 (1955).

16. Haig, C., Hecht, S., and Patek, A. J., "Vitamin A and Rod-Cone Adaptation in Cirrhosis of the Liver." Science, 87(2267): 534-536 (1938).

17. Halperin, M. H., Niven, J. I., McFarland, R. A., and Roughton, F. J. W., "Variations in Visual Thresholds During Carbon Monoxide and Hypoxic Anoxia." Federation Proc., 6(1): 120 (1947).

18. Hammond, C. E., and Lee, R. H., "Criteria for Scoring Dark Adaptation Tests." Report #3 on Studies in Aviation Medicine, July 10, 1941, Research Section, Division of Industrial Hygiene, U. S. Public Health Service, Federal Security Agency, Bethesda, Maryland.

19. Heath, W. M., and Finch, D. M., "Effect of Tinted Windshields on Nighttime Visibility Distances." In, Effect of Tinted Windshields and Vehicle Headlights on Night Visibility, HRB Bul. 68, Washington, D. C., National Academy of Sciences—National Research Council, p. 1-15 (1953).

20. Hecht, S., "Rods, Cones, and the Chemical Basis of Vision." Physiol. Rev., 17, 239 (1937).

21. Hecht, S., and Mandelbaum, J., "Rod-Cone Dark Adaptation and Vitamin A." Science, 88(2279): 219-221 (1938).

22. Hecht, S., and Mandelbaum, J., "The Relation between Vitamin A and Dark Adaptation." J. A. M. A., 112(19): 1910-1916 (1939).

23. Hecht, S., and Mintz, E. U., "The Visibility of Single Lines at Various Illuminations and the Retinal Basis of Visual Resolution." Jour. Gen. Physiol., 22(5): 593-612 (1939).

24. Hecht, S., and Mandelbaum, J., "Dark Adaptation and Experimental Vitamin A Deficiency." Am. Jour. Physiol., 130(4): 651-664 (1940).

25. Hecht, S., and Hsia, Y., "Dark Adaptation Following Light Adaptation to Red and White Lights." Jour. Opt. Soc. Am., 35(4): 261-267 (1945).

26. Holladay, L. L., Jour. Opt. Soc. Am., 12, 271 (1926).

27. Lauer, A. R., "An Experimental Study of Glare Susceptibility." Am. Jour. Opt., 13(6): 200-207 (1936).

28. Luckiesh, M., and Moss, F. K., "Glare from Sodium Light." Tr. Illm. Engin. Soc., 30(8): 602-610 (1935).

29. McFarland, Ross A., Domey, Richard G., Warren, A. B., and Ward, D., "Dark Adaptation as a Function of Age." (To be published.)

30. McFarland, R. A., Graybiel, A., Liljencrantz, E., and Tuttle, A. D., "An Analysis of the Physiological and Psychological Characteristics of Two-Hundred Civil Airline Pilots." Jour. Aviation Med., 10: 2-52 (1939).

31. McFarland, R. A., Halperin, M. H., and Niven, J. I., "Visual Thresholds as an Index of Physiological Imbalance During Anoxia." Am. Jour. Physiol., 142 (3): 328-349 (1944).

32. McFarland, R. A., Roughton, F. J. W., Halperin, M. H., and Niven, J. I., "The Effects of Carbon Monoxide and Altitude on Visual Thresholds." Jour. Aviation Med., 15(6): 381-394 (1944).

33. McFarland, R. A., Halperin, M. H., and Niven, J. I., "Visual Thresholds as an Index of the Modification of the Effect of Anoxia by Glucose." Am. Jour. Physiol., 144(3): 379-388 (1945).

34. McFarland, R. A., Halperin, M. H., and Niven, J. I., "Visual Thresholds as an Index of Physiological Imbalance during Insulin Hypoglycemia." Am. Jour. Physiol., 145(3): 299-313 (1946).

35. McFarland, R. A., and Fisher, M. B., "Alterations in Dark Adaptation as a Function of Age." Jour. Gerontol., 10(4): 424-428 (1955).

36. McFarland, R. A., Domey, R. G., Warren, A. B., and Ward, D., "Dark Adaptation as a Function of Age and Tinted Windshield Glass." (To be published.)

37. McFarland, R. A., and Wolf, E., "The Influence of Tinted Windshield Glass upon Visual Acuity, Glare, Stereopsis, and Light Shock." (To be published.)

38. Miles, P. W., Arch. Ophthalm., 51, 15 (1954).

39. Murrah, J. H., "Atlanta Lighting Cuts Crime 50 Percent, Averts 1,700 Traffic Accidents: It Is First Big City To Be Lighted by Illumination Engineering Society Standards." Am. City, 67(9): 157 (1952).

40. Peckham, R. H., "Effect of Exposure to Sunlight on Night-Driving Visibility." In, Night Visibility, HRB Bull. 56, Wash. D. C., National Academy of Sciences—National Research Council, p. 17-24 (1952).

41. Pennsylvania Turnpike Joint Safety Research Group, Eckhardt, P. L., (eds.) Accident Causation., Swissvale, Pa., Westinghouse Air Brake Co., (Sept., 1954).

42. Pinson, E. A., "Dark Adaptation in Army Air Corps Personnel." War Department, Air Corps, Material Division, Experimental Engineering Section, Memorandum Report No. EXP-M-54-653-51, (August 28, 1941.)

43. Robertson, G. W., and Yudkin, J., "Effect of Age upon Dark Adaptation." Jour. Physiol., 103:1-8 (1944).

44. Roper, V. J., "Nighttime Seeing through Heat Absorbing Windshields." In, Effect of Tinted Windshields and Vehicle Headlighting on Night Visibility, HRB Bull. 68, p. 16-30 (1953).

45. Ryan, T. A., "Fatigue and Effort in Relation to Standards of Performance and Systems of Payment." Internat. Labour Rev., 65(1): 44-63 (1952).

46. Shrenk, L. J., "Effect of Light Changes on Traffic Accidents Shown in Detroit Lighting Report." Illum. Engin., 42(9): 890-892 (1947).

47. Seburn, T. J., "Street Lighting - Traffic Accidents - Crime." Illum. Engin., 482-483 (1951).

48. Simonson, E., Blankstein, S., and Carey, E. J., "Influence of Selected Spectral Distribution on the Glare Effect, Studied by Means of Dark Adaptation." Am. Jour. Ophthalm., 28(7): 712-724 (1945).

49. Smeed, R. J., "Some Factors Influencing the Road Behavior of Vehicle Drivers." Advancement of Science, 9(36): 395-404 (1953).

50. Stiles, W. S., Proc. Roy. Soc., B, 105, 131, 129.

51. Torkelson, H. P., Fisk, L. B., and Brown, C. W., "Some Results from the Use of a Glare Recovery Apparatus with College Students." Jour. Applied Psychol., 25(4): 447-457 (1941).

52. Wald, G., and Steven, D., "An Experiment in Human Vitamin A Deficiency." Proc. Nat. Acad. Sciences, 25(7): 344-349 (1939).

53. Wolf, E., "Effects of Exposure to Ultra-Violet Light on Human Dark Adaptation." Proc. Nat. Acad. Sciences, 32(8): 219-226 (1946).

54. Wolf, E., "Optical Glass and Eye Protection." Ophthal. Foundation, N. Y. (1951).

55. Wolf, E., and Zigler, M. J., Jour. Opt. Soc. Am., 40, 211, 1950: 130 (1951).