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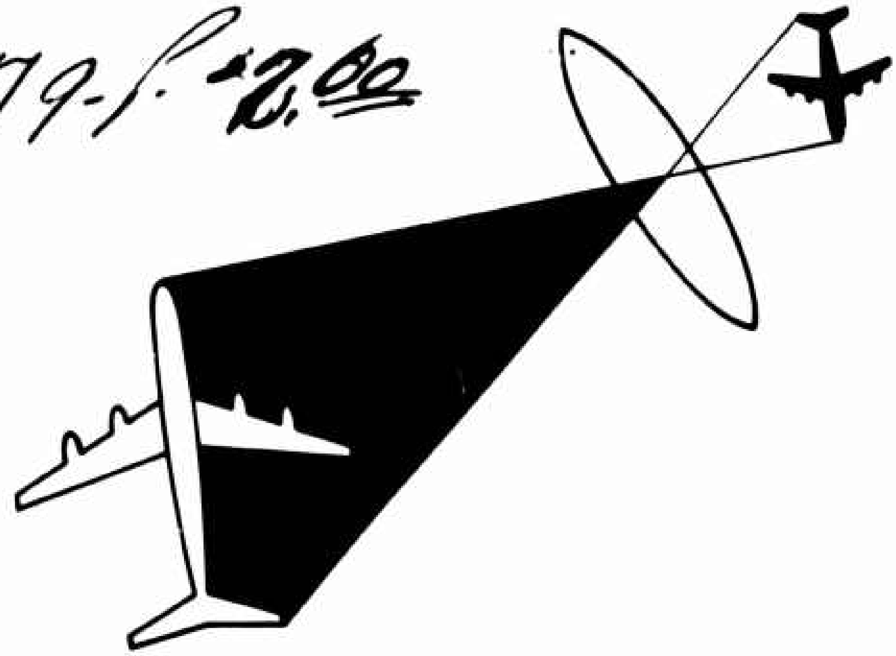

THE ROLE OF OPTICAL DEVICES IN MID-AIR COLLISION PREVENTION

PROJECT NO. 110-512R

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ABSTRACT

This report summarizes that portion of a research program on visual mid-air collision avoidance techniques which deals with the feasibility and efficacy of various optical aids. Literature relevant to promising optical aids is reviewed, including that on: sunglasses, visors, goggles, telescopes, binoculars, periscopes, sighting levels, collimated reticles, rear-view mirrors, and closed-circuit television.

No one optical aid can provide adequate assistance over the entire range of visual conditions found in flight. Sunglasses provide a number of advantages including the reduction of glare and the immediate and cumulative effects of exposure to high brightness levels. Telescopes and binoculars can assist in making inferences about detected aircraft, but will not materially assist in searching. Rear vision may be increased by mirrors, but mirror vibrations and vibrations acting upon the pilot degrade visual performance.

Pilots are encouraged to use light filters (sunglasses or sun visors), to install and use rear view mirrors when possible, and to use sighting levels to aid judgments of relative altitude.

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INTRODUCTION

By the beginning of World War I, the performance characteristics of aircraft had improved to the point where altitudes of 20,000 feet and above were attainable. At this time medical research interest shifted from examining and selecting pilots to determining the physiological effects of anoxia on the various senses, particularly on vision.

The first studies of the various visual symptoms found at high altitudes were concerned with determining whether they were caused by lack of oxygen or by reduced barometric pressure. Later studies measured the effects of anoxia on such functions as visual acuity, accommodation, convergence, night vision, and retinal sensitivity.

With the advent of trophy races in the early 1920's, other symptoms of physiological stress appeared, such as blackout during high speed turns. Aircraft performance was already reaching the point that it imposed stresses upon the pilot that were far removed from his normal environment. One of the major effects of such stress is a reduction or loss of visual capability. Considerable research has been conducted in an attempt to understand and overcome or negate the effects of these stresses.

With the onset of World War II, visual research was given new impetus. Problems that were an irritation in peacetime became vitally important in wartime. The old problems of air-to-air search, glare, anoxia, distance judgment, depth perception, peripheral vision, and night vision had new meanings and therefore were re-examined. New quantitative measurements were made to bring existing data up to date as well as to bridge gaps in our knowledge.

The transition from reciprocating engines to turbine engines since World War II has exaggerated some of the older problems and created new ones. The high closing speeds of some modern aircraft may minimize the value of vision in avoiding collisions. At such high speeds the time between visual detection and possible collision is significantly less than the combined detection, interpretation, pilot reaction, and aircraft response times. Further, the high climb rates of modern jet aircraft subject the pilot to rapid changes in both type and direction of glare and to rapid fluctuations in brightness contrasts.

Prolonged flight at high altitudes has created a new and unusual set of visual problems. The increased amount of ultraviolet, the reversed distribution of light, the higher contrast ratio between light and shaded areas, and the lack of visual detail in the homogeneous blue sky found at high altitudes all tend to exact their toll on the visual efficiency of a pilot.

Until a reliable, accurate, and reasonably priced electronic collision-avoidance system becomes available, the pilot will tend to rely chiefly on his visual capabilities. Even with the development of electronic equipment, the pilot may still take recourse to direct vision when taking off and landing, judging the attitude of his aircraft, and detecting and identifying ground objects and (to some extent) other aircraft. Visual flight has the advantage of being more natural, easier, and less tiring than instrument flight, as well as less subject to inflight failures. In addition, the pilot can distinguish between different aircraft and different objects on the ground as no electronic equipment can.

A pilot's vision is affected or limited by a number of variables. One source of limitation is his individual visual equipment. A second source is cutoffs imposed by the canopy, windshield, and general configuration of his aircraft. Another is the state of the atmosphere: the transmissivity, general weather conditions, time of day, type and altitude of cloud cover, and so forth. Finally, there is the variable with which this paper deals: the use of such optical aids as sunglasses, sun visors, goggles, binoculars, periscopes, and rear view mirrors. The specific contract task with which this report is concerned was to:

> Assess the feasibility of using, adapting, or designing optical devices to supplement pilot visual ability in evaluating collision threats and determining safe avoidance maneuvers.

The most promising optical aids that have been suggested at one time or another are reviewed in this paper.

SUNGLASSES

Pilots commonly wear sunglasses to reduce eyestrain and discomfort caused by high levels of illumination. The effects of sunglasses on vision, and their advantages and disadvantages, therefore warrant review.

Evaluation of the effects of sunglasses on vision must consider the characteristics of normal vision. Some of these characteristics are presented in the appendices. Particularly pertinent to the present discussion are the following facts:

1. Visual acuity increases as level of ambient illumination increases.

2. Prolonged exposure to high brightness levels adversely affects scotopic (nighttime) vision and probably degrades photopic (daytime) vision.[1]

   a. These effects are small for photopic vision, becoming increasingly significant as the level of post-adaptation illumination decreases.

   b. The effects on scotopic vision are considerable, delaying the onset and the final level of dark adaptation.

   c. The effects are cumulative.

3. Even brief exposure to glare significantly reduces visual efficiency, especially under scotopic conditions.

The U. S. Forest Service, in investigating the detection of forest fires under various conditions of haze, found that ordinary colored filters have little or no value for smoke detection except to reduce glare and intense brightness that may cause eyestrain and discomfort (Byram & Jemison, 1948). McArdle & Byram (1936) developed a smoked glass (neutral) goggle with a transmission of 26 per cent. These optically correct goggles relieved eyestrain with no apparent change in visual acuity.

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[1] This point is particularly pertinent to one of the conclusions of this section. A complete discussion will be found in Appendix B.

Byram (1942) reported that a neutral polarizing screen, or one combined with a red filter, was more effective in light haze than were colored filters. According to Byram and Jemison (1948), visibility distance using this "haze-cutter" is increased from 20 to 50 per cent for smokes viewed at right angles to the sun, depending upon atmospheric clearness. Figure 1 illustrates the visibility distance of two types of smoke with and without the "haze-cutter"; Figure 2 shows the visibility distance of smoke at various angles to the sun. The "haze-cutter" is based on this principle: if particles suspended in the atmosphere are very small with respect to the wave lengths of light, scattering is by resonance in which the light rays, scattered at right angles to the original beam, are completely plane-polarized but of one-half the intensity of the unpolarized light which is scattered in either a forward or backward direction. Therefore, a polarizing screen, oriented to exclude polarized light, will reduce the apparent intensity of air-light without decreasing the intensity of unpolarized light (emitted or reflected) from some object, thereby enhancing contrast. If light from an object is plane-polarized in a plane different from that of air-light, reorienting the polarizing screen in the same plane as the polarized light from the object would again enhance contrast. In order to reorient the plane of the polarizing screen, a rotatable screen would be required.

The polarizing screen is the only filter that (a) decreases the level of illumination at the eye, and (b) increases the apparent contrast between an object and its surround, thereby increasing the probability of detection. Using the "haze-cutter," Byram found that on days when white smokes (unpolarized light) could be seen 10 miles, approximately 4 miles were gained by using the haze-cutter.

Sunglasses made with a red filter[1] between two rotatable, polarizing lenses might prove to be superior to ordinary sunglasses in detecting other aircraft. Rotating both lenses so that their polarization planes are parallel with respect to an object's polarization plane (if the light from the object is polarized) would maximize the object's contrast with its surround. Rotating the polarization plane of one lens so that it is perpendicular with respect to the other would maximize their filter effect. By adjustment of the angle between the two polarization planes the pilot could select the amount of filtering he found most comfortable for

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[1] Investigation might be necessary to determine that a red filter rather than some other color would indeed be best, and to determine the acceptable color tolerances.

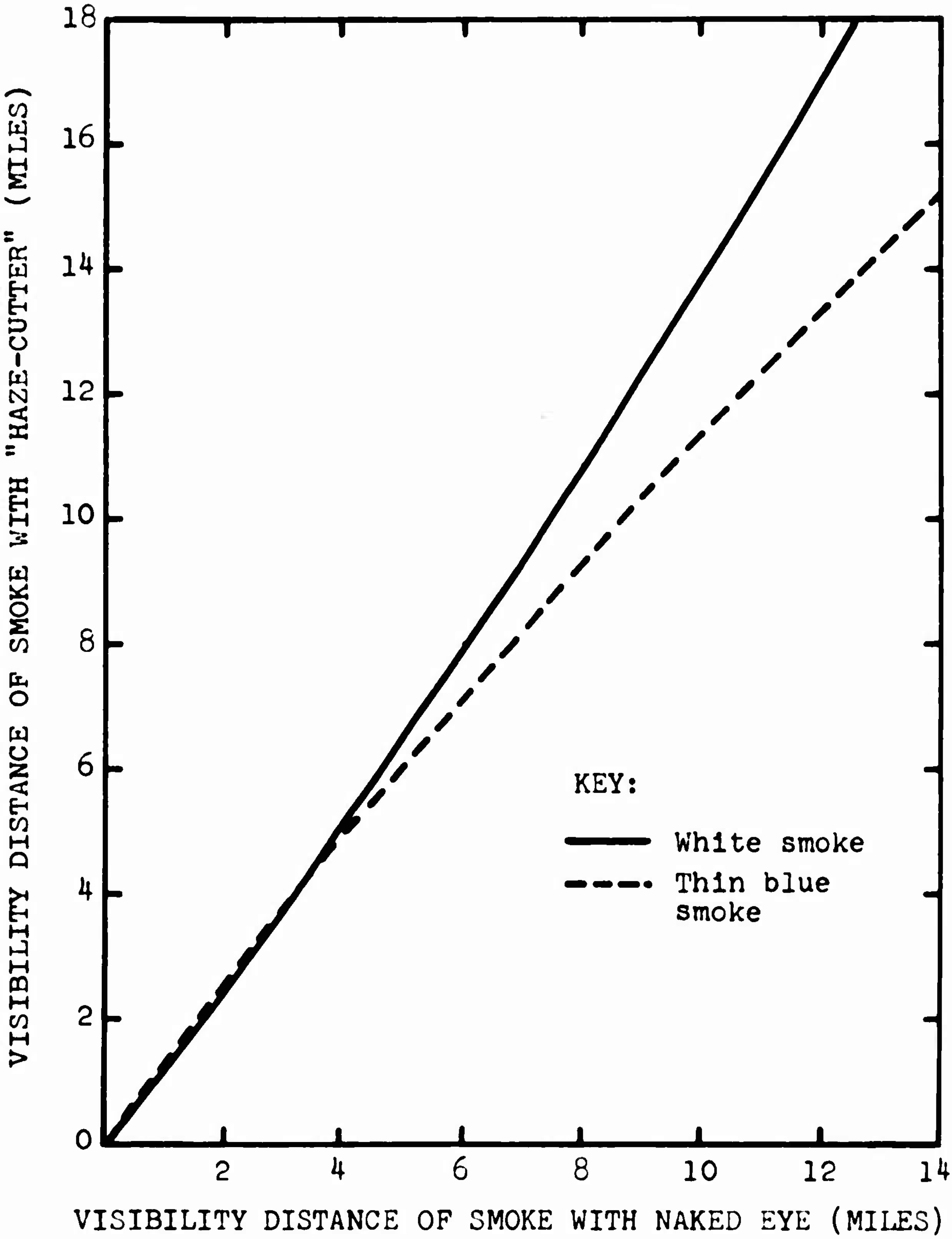

Fig. 1. Computed visibility distance of a small white smoke and thin blue smoke as viewed with and without a neutral polarizing screen combined with a red filter (haze-cutter). For the thin blue smoke, the polarizing screen is reversed to transmit polarized air-light. (After Byram & Jemison, 1948.)

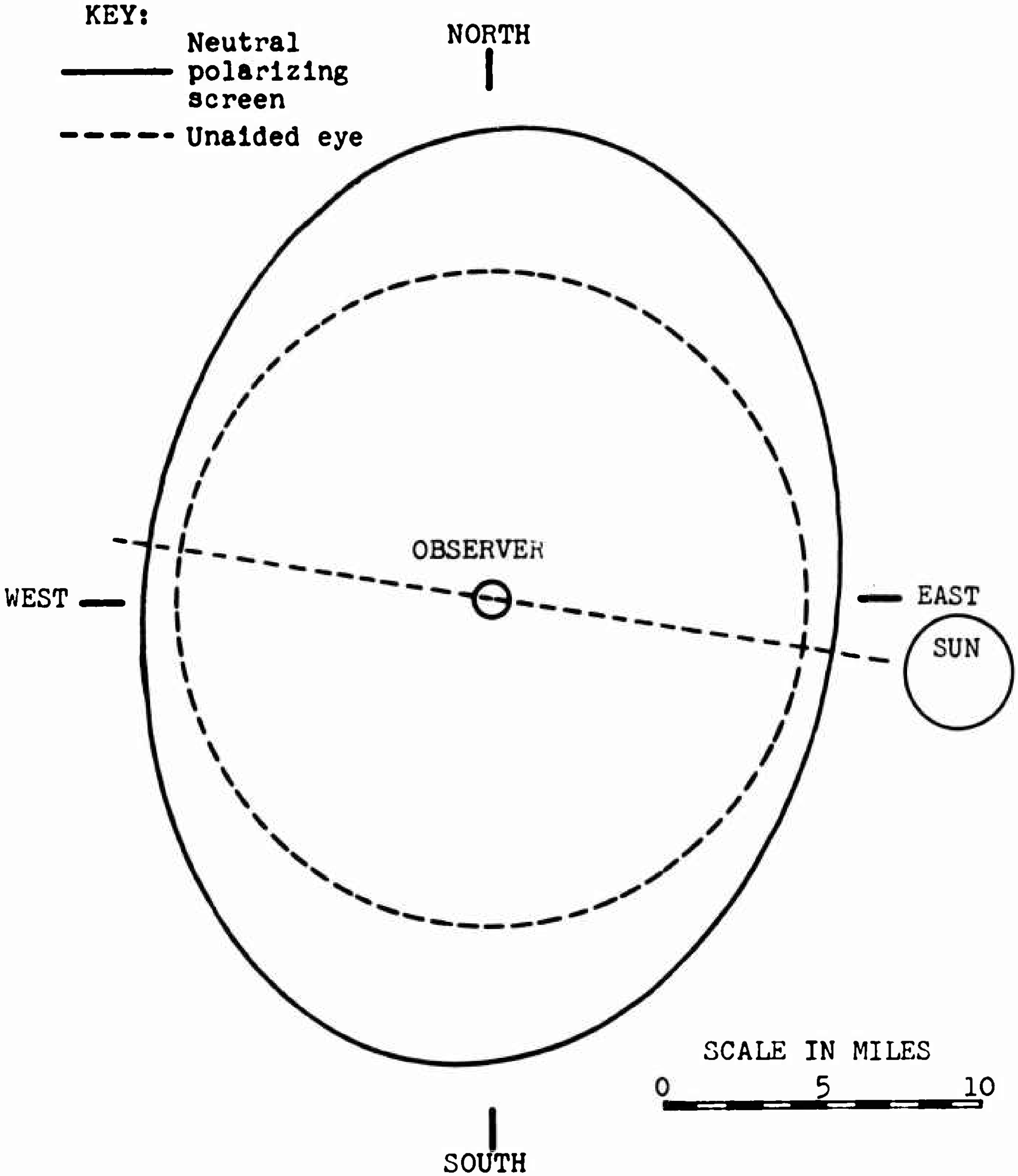

Fig. 2. Visibility distance of a white smoke viewed with the unaided eye and with a neutral polarizing screen (haze-cutter). Curves are computed for 8 a.m. August 21 at latitude 35°. (After Byram & Jemison, 1948.)

a given level of illumination. Application of the "haze-cutter" principle to pilots' sunglasses therefore appears worthy of further investigation.

In general, detection threshold is a function of two variables, namely, (a) visual acuity and (b) ability to see contrast between stimulus and surround. Another way of looking at detection is that, in most situations, it is a task based upon a reaction to a change. The detection threshold would be defined, therefore, as the amount of change required for the occurrence of the change to be reported accurately 50 per cent of the time. Here we are concerned with the change in intensity or brightness (ΔI) of the distant stimulus. The amount of change necessary before detection occurs, however, depends on the intensity of the stimulus surround (I). According to Weber's Law, this ratio is a constant ($\Delta I/I$-K). Unfortunately, Weber's Law does not necessarily hold over the entire intensity range (see Appendix); and since it does not, placing a light filter between subject and stimulus could lead to an increase in detection threshold with decreasing illumination, that is, the detectability of low-contrast objects would decrease.

Blackwell (cited in December, 1960) tested this idea in the laboratory and found that detection thresholds increased under low levels of illumination when subjects wore sunglasses. When objects were viewed through tinted windshield glass (transmissivity of 70 per cent) under low levels of illumination, Blackwell (1954) found a 23 per cent loss in detection distance. Further, as distance for detection without tinted filters became smaller because of reduction of target size or luminance level, the percentage loss in detection distance increased rapidly with use of the tinted windshield glass.

The decrement in scotopic visual efficiency caused by tinted windshield glass has been variously reported as 3 per cent (Doane & Rossweiler, 1955), 6 per cent (Roper, 1953), 20 per cent (Wolf, McFarland, & Zigler, 1960), and 22 per cent (Health & Finch, 1953). These differences are probably due to differences in visual functions measured, type of measurement, different levels of ambient lighting, and differences in experimental techniques. Despite these differences, there is apparent agreement that as luminance levels decrease there is a reduction in visibility, and that the reduction is more serious at scotopic than at mesopic (twilight) luminance levels.

Wolf et al. (1960) found that the increase in the threshold for recognition of a test stimulus corresponded exactly to the brightness loss produced by tinted windshield glasses. When visual acuity was measured using Landolt rings, the gaps could be seen only if they were from 10 to 20 per cent larger than for normal vision. Depth perception, as measured with a Verhoeff stereopter, showed a 25 to 35 per cent loss when the test stimulus was viewed through tinted windshield glass. Recovering from a sudden exposure to a blinding light and regaining of the previous sensitivity level was not enhanced by the tinted windshield glass. All tests showed a reduction in visual efficiency corresponding to the physical absorption of radiant flux by the filter in front of the eyes. No improvement of any sort was found when tinted windshield glass was used.

The findings of the above studies are generally applicable to the use of sunglasses. Visual acuity, however, may be somewhat poorer through windshields than through sunglasses, for these reasons:

1. Windshields are not optically ground for a given individual's eyes;

2. Differences in spectral transmission; and

3. Prismatic effects introduced by curvature of the windshield and differences in refraction of two laminated sheets of glass.

Allen (1961) investigated visual performance through five readily available ophthalmic filter glasses, five identical filter glasses uniformly coated to yield 10 per cent transmission, and five other identical filter glasses with a gradient density coating which transmitted 0.5 per cent at the top, 10 per cent at the center, and the normal transmission of the sunglass itself at the bottom. An atmospheric chamber was used to simulate flight with adverse glare under clear and foggy conditions. Luminances of approximately 7000 foot-lamberts and 400 foot-lamberts were provided in the chamber. The far point test target was a $1/2^{\circ}$ white spot, which could be varied in brightness by the subject relative to the surround. The near-point target was a randomly presented number target set in a Link Trainer instrument panel. Panel luminance ranged from 0.1% to 0.43% of chamber luminances. The subject's task was to adjust the brightness of the far test spot to be just noticeably brighter and just noticeably dimmer than the background wall. Upon an auditory signal he was required to look down and correctly identify a number randomly presented on the instrument panel. The response was the time required to correctly identify the number.

The summarized data for both near and far target tasks are presented in Fig. 3. Visual performance through gradient

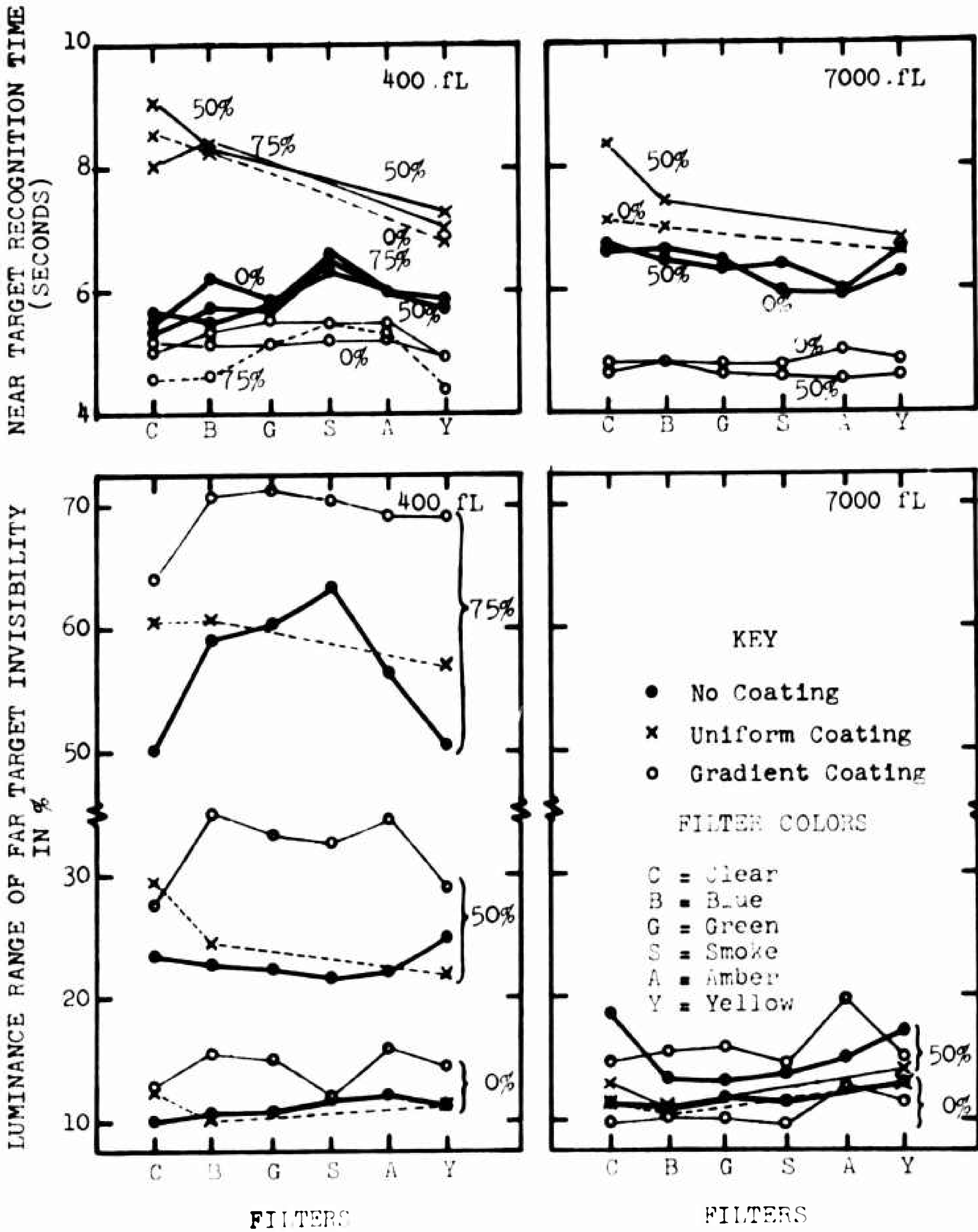

Fig. 3. Average visual performance of six subjects using sunglasses of different types and colors to view near (upper curves) and far (lower curves) targets through fogs of 0, 50, and 75% density in low and high luminance levels. (After Allen, 1961.)

density sunglasses was superior, at both levels of illumination, for recognizing near target detail. The average reaction times required to identify correctly the randomly presented number on the instrument panel for both levels of illumination were:

Gradient = 0.56 seconds
No sunglasses = 0.599 seconds
Ordinary sunglasses = 0.609 seconds
Uniform coating = 0.760 seconds

For far target detail, visual performance[1] was impaired by all sunglasses at low levels of illuminance. At high levels of illumination, gradient density filters were slightly superior to no sunglasses. Of the colors of filter used, amber yielded slightly superior performance at high levels of illumination, probably because it had the lowest transmission.

The subjects' comments are interesting. Any gradient density sunglass was well liked. However, yellow filters at high luminances drew unfavorable comments from all subjects. Serious difficulties in matching the far target with its surround occurred with amber sunglasses. Minor color differences occurred with blue and with green. Even the slightest speck of dust caused a decrement in performance.

In a series of experiments with goggles, Kohler (1962) investigated how the visual system learns to produce an effective picture of the world when images are systematically distorted by specially constructed goggles. He had subjects wear goggles in which the left half of each lens was blue and the right half yellow. The experimental results showed that the visual system quickly adapted to these different color stimuli as long as the colors were invariably associated with a particular situation, that is, left blue and right yellow.

Color stereopsis produced by squint glasses (prismatic lenses whose bases face on opposite directions) showed not the slightest adaptation, possibly because of the random and unpredictable relation between color and spatial displacement. Adaptation was rapid to color fringes and line distortions produced by prismatic lens whose bases face in the same direction. Several weeks were required, however, to

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1 This was measured by the "luminance range of far target invisibility in %" which was defined as the luminance of the far target when just noticeably brighter than the background minus its luminance when just perceptibly darker, divided by the upper luminance and multiplied by 100 to yield a percentage figure.

adapt to the complex variable distortions produced by head-goggle movement or by eye movement behind the goggles. Thus, according to Kohler's findings, if distortions of the real world (color or dimensional) are invariant, the visual system will adapt itself to the new situation. However, if the lenses produce random distortions, as is the case with many inexpensive plastic sunglasses, adaptation will probably not occur.

On the basis of all of the studies surveyed, it may be concluded that the interposition of a filter between an observer and his visual environment increases his detection threshold. The increase in detection threshold corresponds exactly to the brightness loss produced by the filter. Under photopic conditions the effect is small, becoming increasingly more serious as the level of illumination decreases. At mesopic (twilight) and scotopic luminance levels, the increase in detection threshold is so large that the use of filters is contra-indicated. Due to atmospheric transmissivity, the increase in detection threshold is greater for far objects than for near objects under both photopic and scotopic conditions.

Prolonged exposure to high ambient illumination has two effects: (a) it produces eyestrain and fatigue, and (b) it reduces subsequent scotopic visual efficiency. The use of a filter device reduces or eliminates these two effects. Under photopic conditions, the reduction in eyestrain and fatigue usually more than compensates for the slight increase in detection threshold. Thus, it may be safely concluded that, under photopic conditions, the advantages of wearing some sort of filter device greatly outweigh the disadvantages.

On the basis of these conclusions, the following recommendations are made regarding sunglasses:

1. Pilots should wear sunglasses whenever flying at high altitudes, or above cloud cover, or on clear, sunny days. Glasses should be removed when moving from a brightly illuminated situation to a dimly lighted one, such as might occur when descending through a heavy cloud cover.

2. Whenever there is a chance of exposure to high levels of illumination for over an hour, as for example, for recreation at the beach or snow skiing, pilots should wear sunglasses. This

requirement is particularly important for night-flying pilots and those over 40 years of age.[1]

3. Sunglasses should not be worn when flying in or under heavy overcast conditions.

4. Sunglasses should not be worn during twilight or at night. This is particularly important for pilots over 40.

5. Sunglasses should not be worn as a protection against nighttime glare, except on the ground and in the presence of high-intensity light sources.

The following general guidelines should be observed in selecting and using sunglasses:

1. The glass should be of standard ophthalmic quality, without optical distortion, and ground to individual prescription if correction is required.

2. Preferably, the color should be some neutral shade. However, individuals can make adequate adjustments to any color filter.

3. Preferably, the sunglass should be gradient density coated for maximum comfort, that is, 1 per cent transmission at top, 10 per cent at center, 90 per cent at bottom. If gradient coating is not used, then over-all transmission of 5 to 10 per cent is recommended.

4. Sunglasses should be kept free of dust, dirt, grease, and smudges if they are to aid rather than hinder visual performance.

Sunglasses are a relatively inexpensive, commonly used optical aid. However, there are precautions to be exercised in their selection and use if maximum benefit is to be derived from them.

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[1] There is an increased sensitivity to glare after age 40. The section on "glare" in Appendix B presents a discussion of the effects of age on visual functions in glare conditions.

Sun visors have been used primarily on high-altitude flights of military aircraft requiring pressure suits, oxygen masks, and helmets. When not needed, a helmet-mounted visor can be pushed up out of the way. Removal of sunglasses on the other hand, first requires removal of oxygen mask and helmet. At least one sun visor has been designed which protects the pilot from veiling glare[1] when placed in a half-raised position, while in the fully lowered position it protects the pilot from dazzle and scotomatic glare, yet does not interfere with his view of the interior of his cockpit from under the bottom of the visor (Whiteside, 1957).

The U. S. Air Force (Wulfeck, Weisz, & Raben, 1958) has used three types of helmet-mounted visors:[2] (a) a cone-shaped visor with short radii of curvatures, (b) a cylindrical visor with a relatively long radius of curvature, and (c) a V-shaped visor. Among the visual problems created by these visors are: (a) restrictions to the field of view, (b) optical distortions produced by the visor's shape and material, and (c) distortions caused by fogging and the methods used to eliminate fogging.

The restriction placed upon the field-of-view by Air Force visors results not only from the size of the visor, but also from the helmet design, the high altitude suit, oxygen mask and other equipment worn by the pilot, and from limited head mobility in military cockpits. As shown in Fig. 4, the largest visual field is obtained with the relatively large radius cylindrical visor. The cone and V-shaped visors are more restrictive. For civilian use, however, sun visors could be developed which would place little or no restriction on the field-of-view. Presumably, too, there would seldom be distortions caused by fogging.

The possibility of distortion of the visual field by the visor's design and materials is of some consequence. Because of the shape and nature of visors, they are usually formed from plastics. Plastics generally have poorer optical characteristics than ground optical glass. Although the surfaces

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[1] See Appendix B for a discussion of the types of glare.

[2] The light transmissions of these visors are too high for them to be considered "sun" visors. However, much of the discussion which follows is equally applicable to visors with lower transmissions.

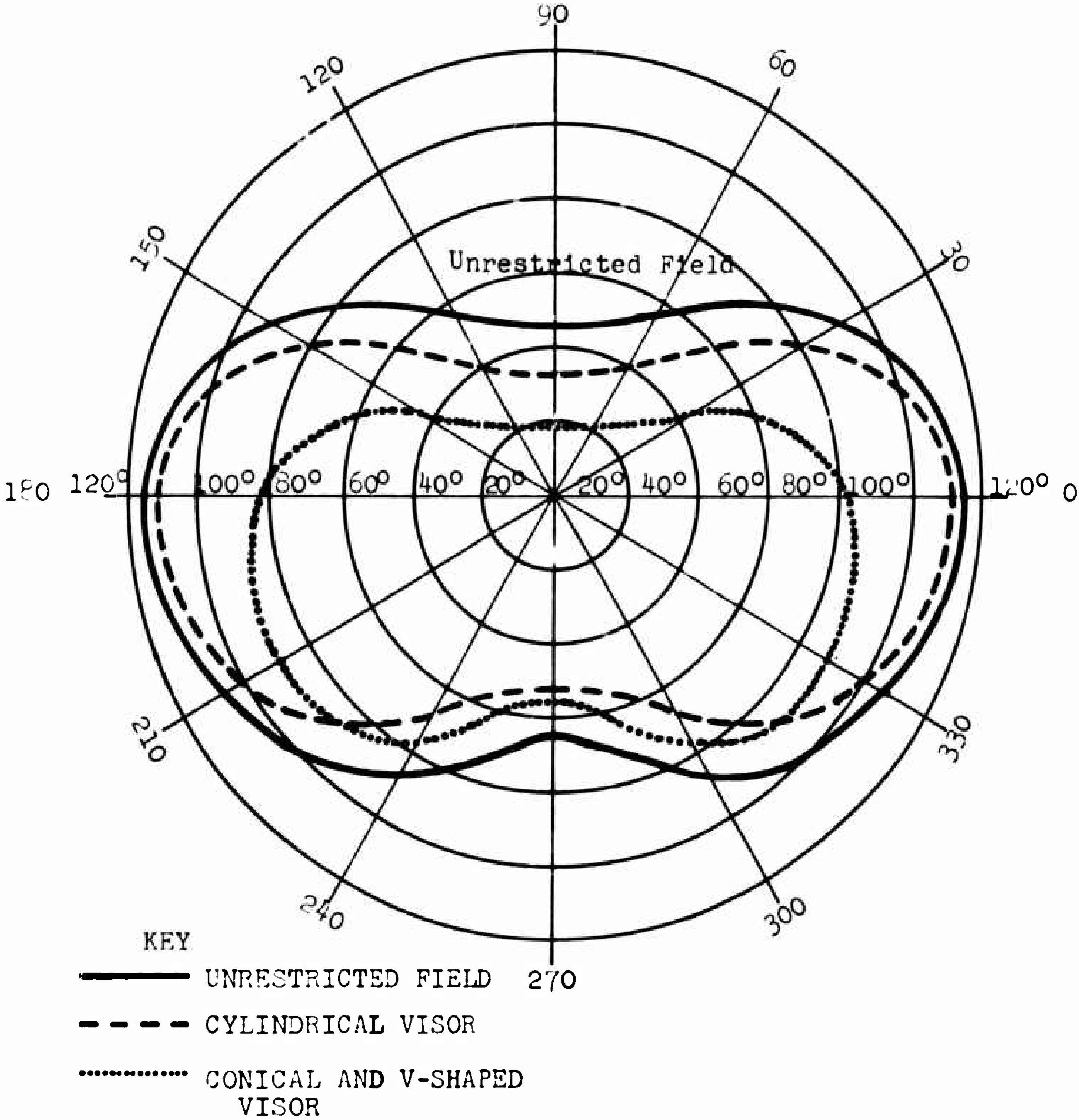

Fig. 4. The visual field without a helmet-mounted visor compared to the field with such visors. (After Wulfeck et al., 1958.)

of the sheets of plastic are parallel, a refractive component results from both the curvature and thickness of the visor. The refractive component may be responsible for a small loss in visual acuity and, if the visor is worn long enough, may produce eyestrain. Eyestrain may also become severe if there are marked changes in prismatic power in adjacent vertical areas of the plastic visor. However, a limited amount of horizontal prismatic imbalance can usually be tolerated.

The radius of curvature considerably influences the visor's refractive component. In general, both refractive and space distortion effects decrease in severity as the radius of curvature is lengthened. On this basis, the V-shaped visor would be ideal; but unfortunately it permits excessive reflections, since light may enter one side of the visor, cross over to the far side, and reflect into the wearer's eyes. Because these reflections are from flat surfaces, the images are visible and meaningful, and hence may distract or annoy the wearer. Although reflections occur with curved visors, they are not meaningful and, therefore, are less distracting. The interference produced by these reflections is greatest when the pilot is scanning the sky casually, not when his eye is fixated on objects of interest. Presently available antireflection coatings fail to remove these reflections.

The soft plastic of which visors are made has little resistance to distortion-producing abrasions. They also easily acquire an electrostatic charge which attracts dust particles. Experience indicates that sun visors tend to be handled with considerably less care than sunglasses or eyeglasses, resulting in abrasion, warping of the radius of curvature, accumulation of oil films, and other distortion-producing influences.

Like optical sunglasses, the transmission of uniform density sun visors should be between 5 and 10 per cent. Gradient density sun visors should have a transmission of 1 per cent at the top, 10 per cent at the center, and approximately 90 per cent at the bottom of the visor. Improvement of the optical quality of plastic by rigidly controlling sheet thickness and eliminating prismatic power differences (especially in the vertical plane) in the plastic sheet would considerably increase the general usefulness of the plastic sun visor. Hardening of the plastic surfaces is also desirable.

Various types of opaque visors have been used more or less successfully to protect the eye from excessive illumination. The British Army used movable louvered eye shades in the African desert to reduce both direct and reflected sun glare. These eye shades protect against veiling glare and, when looking near the sun, against scotomatic glare.[1] Although visual acuity is presumably not affected, the presence of the louvers may decrease the detection probability by restricting the field of vision. Although louvered eye shades protect against glare, they do not reduce the level of illumination to which the eye is exposed. As a result, under some conditions they are less effective than sunglasses.

In summary, then, it can be seen that principally because of the inherent disadvantages of plastics, sun visors are less useful, generally, than ground optical sunglasses. However, since they eliminate the adverse effects of veiling glare without placing a light filter in front of the eyes, some pilots may prefer them. Except in cases of strong personal preferences, or when helmets are used, sunglasses are to be preferred. Some pilots might prefer a combination of optical sunglasses and visor with the visor kept permanently in the half-raised position. In such a condition, the visor should be of uniform density plastic. Lack of desirable optical qualities and resistance to damage of the plastic would not be critical with such usage.

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1 Appendix B contains a discussion of the types of glare.

GOGGLES

In the early days of aviation, with its open cockpit aircraft, goggles were used extensively to protect the eyes from wind and from airborne particles. Today, their use is mainly restricted to the few remaining open-cockpit aircraft used in crop dusting. The special flying conditions met in crop dusting require maximum visual acuity and protection of the eyes from the chemical action of the dusts and sprays used. Because of the individualistic nature of crop dusting, the selection of goggles and type of filter lens is best left to the individual pilot.

In general, both open-face plate and individual eye lens types restrict the visual field, especially peripheral vision. Because of the restriction in vision, goggles should be used only where the situation requires protection of the eye from impact injury and effect of wind, cold, and so forth. The recommendations for the type of lens or plastic face plate are the same as for sunglasses and sun visors.

OPTICAL TELESCOPES (MONOCULAR AND BINOCULAR)

Optical telescopes have been used by pilots to extend their visual range in searching for, detecting, and identifying other aircraft. The three processes, although different, slight overlap:[1] search involves scanning a large field of view, detection involves primarily visual acuity, and identification involves both space perception and recognition of the relevant and significant characteristics of an object. Detection and identification are both affected by experience with a given classification of objects. In some instances this experience may be the most important factor.

Because the field of view is smaller with a telescope than with unaided vision, more eye fixations are required to survey the same search area, thereby increasing search time. Shifting back and forth between aided and unaided viewing also increases search time. The increase in range afforded by a telescope must be weighed against the increased search time. To be of value to the pilot, aided search must take less time than that required for the aircraft to travel the distance between the aided and the unaided visual ranges, plus the time required to complete the unaided visual search. Thus, the faster the aircraft, the less useful is a telescope for search purposes.

In a comparative test of binocular versus unaided visual search (Great Britain Air/Sea Warfare Devel. Unit, 1948), observers were required to search the seas for a radar training buoy. Half of the subjects used binoculars of 8-power magnification, while the others used unaided vision. Both groups were given the same sector to search, from identical lookout positions (bombardier or co-pilot's position). The results indicated that unaided vision missed the target less often than did search with binoculars. When the target was sighted by both lookouts, the average sighting range was greater with binoculars. Other sources (Leavitt, 1945; Lamar, 1946; Smith, 1960) indicate that unaided search is, in general, more effective than binocular search. Generally, the smaller the field to be searched, the more effective telescopes become. If, however, visibility is less than five miles, they will not appreciably increase sighting range.

On the other hand, if an object of interest has been located by unaided search, the increased range afforded by

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[1] See Appendix A for a more complete discussion of visual space perception.

telescopes is of definite value in identification. Estimating distance poses a problem, however, because the restricted visual field tends to distort the apparent size of distant objects viewed through a telescope (Imber, Stern, & Vanderplas, 1954). Depth perception is independent of magnification, and nearly independent of range (Weiss, 1957).

The selection of type of telescope depends on its use. For binoculars, the prism type (positive objective and ocular lenses with prisms to invert and reverse final image) is generally preferable to the Galilean (positive objective and negative ocular lenses) since they have better eye relief and cover a larger field. The degree of magnification, which to some extent determines the size of the field,[1] depends on the type of use. Lower powers of magnification (probably not exceeding 4X) are to be preferred for searching, whereas higher powers (probably not exceeding 7X) may be used for identification. One study (Verplanck, 1947) found that with hand-held telescopes visual range was not effectively increased with magnifications beyond 6X; with mounted telescopes visual range increased with magnifications up to 20X (the highest power tested).

A large amount of information is available on the magnification of telescopes. In general, visibility is not improved in direct proportion to the amount of magnification. Even when allowances are made for atmospheric conditions, vibration, etc., the increase in range over that of direct vision is not proportionately increased with the magnifying power. A series of nomographs has been prepared (Verplanck, 1947; Duntley, 1948) which show this to be the case especially in hazy atmospheres.

Available experimental evidence does not indicate whether binocular or monocular viewing is superior. One study (Riggs, 1947) indicates that binocular telescopes are superior to monocular telescopes for picking up targets under adverse conditions. The values reported for this superiority have ranged from 10 to 50 per cent for binocular viewing. Also, individuals may be more prone to use binoculars since most people prefer binocular vision.

Characteristics of telescopes differ according to whether they will be used under daylight or nighttime conditions. Since the apparent brightness of the image depends on the transmission characteristics of the optics, it is important to keep the number of air/glass surfaces to a minimum for

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[1] For example, 6- or 7-power binoculars have a clear field of about 120 yards at 1000 yards.

nocturnal use. By coating the glass surfaces with an anti-reflection coating (magnesium fluoride), a gain of 25 per cent in light transmission is possible. While this has little effect on daylight viewing, it improves nocturnal use by approximately 15 per cent (Smith, 1943; Riggs, 1947).

For night binoculars, the diameter of the objective lens should be quite large, because the larger the lens, the greater is its light gathering power. The exit pupil size (the image of the objective formed by the ocular lens) should correspond to the size of the entrance pupil of the dark adapted eye (approximately 8 mm.). For daytime use, the exit pupil size probably need not exceed 4 mm. Eye relief (the distance from last surface of an optical instrument to the plane of the exit pupil of the system) should be of medium length. That is, the ocular lens should be sufficiently far from the eye to keep the instrument from striking the eye, yet short enough to be easily aligned.

For telescopes to be of value to a pilot, a number of conditions must be met (Wulfeck, Weisz, & Raben, 1958):

1. If they are to be hand-held or helmet-mounted, they should be light in weight, preferably no more than two pounds. A light weight is less fatiguing and causes less hand tremor or helmet imbalance.

2. Vibration should be reduced to a minimum.

3. They should be capable of use in a large field about the aircraft, in some cases up to 360 degrees in azimuth: therefore, they should not be so bulky as to strike or interfere with other equipment or procedures.

4. They should permit rapid alternation between aided and unaided viewing.

Three basic types of mountings have been used for telescopes (Wulfeck, Weisz, & Raben, 1958): (a) aircraft mount, (b) helmet mount, and (c) hand-held. Aircraft mounting solves the problem of weight, bulk, hand tremor, and airframe vibration (if mounted properly). Shifting from unaided to aided vision may be difficult, especially in turbulent weather. Helmet mounting solves the problem of hand tremor, vibration, and to some extent buffeting. Helmet mounting permits rapid shifting from unaided to aided vision. Weight and bulk pose a problem, however. Holding the telescope by hand is the least satisfactory type of mount. Generally both hands are required, and even then shifting from unaided to aided vision cannot be accomplished as rapidly as with a helmet mount. For occasional limited use, however, it may be the only practical approach.

In summary, telescopes, either binocular or monocular of less than 4X magnification, may be useful in searching for other aircraft provided: (a) the area to be searched is relatively small, (b) the speed of the aircraft is not too great, and (c) visibility exceeds 5 miles. Telescopes of higher magnification, but not exceeding 7X, may be of some value in identifying other aircraft once they have been located. Helmet-mounted binoculars are preferable if use is frequent; otherwise, holding them by hand may be more practical. Either monocular or binocular telescopes may be used, although most pilots prefer the binocular type. Selection of the type of telescope should also be based on whether it will be used predominantly in daylight, or at night.

The application of the principle of television's "Zoomar" lens to binoculars would enable a pilot to use low magnification while searching for other aircraft and then, upon detection, switch immediately to high magnification for identification. The change in magnification would have to be accomplished in such a way that the target remained in the field of view, which narrows in Zoomar systems.

PERISCOPES

Periscopes have been proposed for use in high-performance aircraft which, for aerodynamic and thermodynamic reasons, would not have windshields (Emerson, 1955a; Emerson, 1955b; Rose & Ripple, undated; J. W. Fecker, Inc., & American Optical Co., undated). They have also been proposed for slower aircraft as a means for searching to the rear (Fisher, 1957). In general, periscopes have sufficient design flexibility (in the placement of objective lens with respect to ocular lens) to be aerodynamically feasible for most aircraft.

Periscopes are generally of two types, ocular and display, which differ with respect to viewing positions of the eye, and in lens construction. In the ocular type, the eye is positioned close to the viewing lens; in the display type, the lens is viewed from a distance of 15 to 18 inches. Optically, the ocular type is the more satisfactory; the position of the ocular lens in relation to the eye permits a larger field of view, while the smaller lens elements permit better correction for aberrations, better resolution and light transmission, and less optical haze. Because the small exit pupil reduces the size of the objective lens, the ocular type would have less aerodynamic drag.

The use of a ground glass or Fresnel viewing lens in the display type results in a loss of resolution and considerable optical haze as compared to a true lens. Stereopsis cannot be obtained with ground glass, but can with a Fresnel or true lens. Use of a ground-glass viewing lens, because of its poor transmission characteristics, would also require low ambient cockpit illumination. In general, the loss of illumination in the display type is greater than in the ocular type. With either type, because of inherent light losses, the object lens would have to be kept free of light-absorbing materials (dust, dirt, oil films, etc.), which can be a difficult task. In the usual optical periscope, the loss in illumination is about two-thirds the total light; about 24 per cent being lost by reflection, and 43 per cent by absorption (Hausman & Stack, 1941). Because of these light losses, periscopes lose their effectiveness in haze and under low levels of illumination.

The exit pupil in the display periscope is limited to about five to seven inches, thereby requiring an objective lens of equivalent size, which, in some installations, may cause considerable aerodynamic drag. If the exit pupil is seven inches, the head (and eyes) can move only a little over two inches laterally from the center position without losing part of the visual field for one eye. In turbulent air, binocular viewing may be difficult. Because of space limitations and the complexity of the optics involved, the visual field of display periscopes is usually restricted to 35 to 45 degrees. In contrast, a stationary ocular periscope has a visual field of approximately 80 degrees, whereas the scanning type can be rotated through 360 degrees.

A drawback to the use of periscopes is the effect their design has on distance cues. The apparent distance of another aircraft, as indicated by the cue of aerial perspective, is increased by the presence of optical haze or poor resolution--a particular weakness of display periscopes. As with optical telescopes, magnification (or minification) will give false cues of object size and of motion parallax. The closer it approaches the observer, the more distorted are the apparent size and angular velocity of an approaching aircraft. On final approaches, pilots tend to overestimate their ground distance with display periscopes and to underestimate with ocular periscopes (Emerson, 1955b). In general, distance estimation tends to be more accurate with ocular than with display periscopes.

Because periscopes reduce the visual field, judgment of motion parallax, which gives the pilot his cues for the best flareout point, must be made from much smaller angular subtenses than is the case with unaided vision. However, successful landings have been made with periscopes even though the error in flareout point was fairly large (Roscoe, 1949). Average error in landing on a designated touchdown spot was 85 feet with periscopes.

Fisher (1957) reported that a target aircraft converging at an angle of 30 degrees could be detected at 3.5 miles using direct vision, whereas with a Farrand Optical Scanner the target aircraft could be detected at a distance of 4.37 miles, when converging in a normally blind area at an angle of 15 degrees. Training, either in learning new cues or assigning new values to old ones, appears to be a factor, since untrained subjects detected the aircraft at 2.2 miles.

The ocular periscope, with its small objective lens and simple optical system, has greater potentiality than the display type as an optical aid to aircraft navigation. As an optical aid, periscopes can be used for search and detection of aircraft converging from normally blind areas. Distance and speed judgments may have too large an element of error to supply useful information. Relative altitude estimation of aircraft flying constant altitude courses, however, may be provided for by superimposing a calibrated collimated reticle on the objective lens.

In summary, properly mounted periscopes could increase a pilot's viewing area by extending coverage to normally blind areas. Periscopes, however, tend to lose their effectiveness under conditions of turbulent air, haze, and low brightness levels.

SIGHTING LEVELS

AND

COLLIMATED RETICLES

Indication of an altitude separation between aircraft is important information for pilots. Some consider it more important than relative course, saying that if two aircraft are at different altitudes, their paths may cross with no danger of collision. One method of determining the approximate relative altitude of another aircraft is the horizon rule-of-thumb: if an aircraft appears on the horizon, it is approximately at the observer's altitude; if above or below the horizon, it is at a different altitude. Military pilots have reported, however, that the horizon rule is unreliable for rendezvous cues at altitudes much in excess of 10,000 feet, with the error in judgment increasing with altitude. Geometric analysis demonstrates that planes seen above the horizon can be level with or even below the observer; planes seen below the horizon are always below the observer. Figure 5 illustrates (with an exaggerated example) why this is so.

Another method of determining the relative altitude of other aircraft is by means of a sighting level. Using the same principle as a surveyor's transit, the sighting level, in its simplest form, consists of a tube, a set of lenses (an objective and an ocular lens with or without magnification), and a horizontal bubble level (see Fig. 6). The objective lens is calibrated with stadia lines. The image of the bubble, reflected upon the objective, permits leveling of the instrument. Aircraft seen directly behind the center stadia line when the image of the bubble is opposite the center line would be at the same altitude. The relative altitude of aircraft seen behind other stadia lines can be estimated from the calibration of stadia lines.

The manufacturer of one inexpensive sighting level claims his instrument to be accurate to one-fifth of a degree.[1] With this particular instrument, at one statute mile, the distance between two stadia lines represents an 80-foot altitude separation. The error could be plus or minus 18 feet. At three miles, the distance between two stadia lines represents an altitude separation of 240 feet (± 54 feet), and at five miles 400 feet (± 90 feet). Thus, an aircraft five miles

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[1] Swift and Anderson, Inc., Boston, Mass.

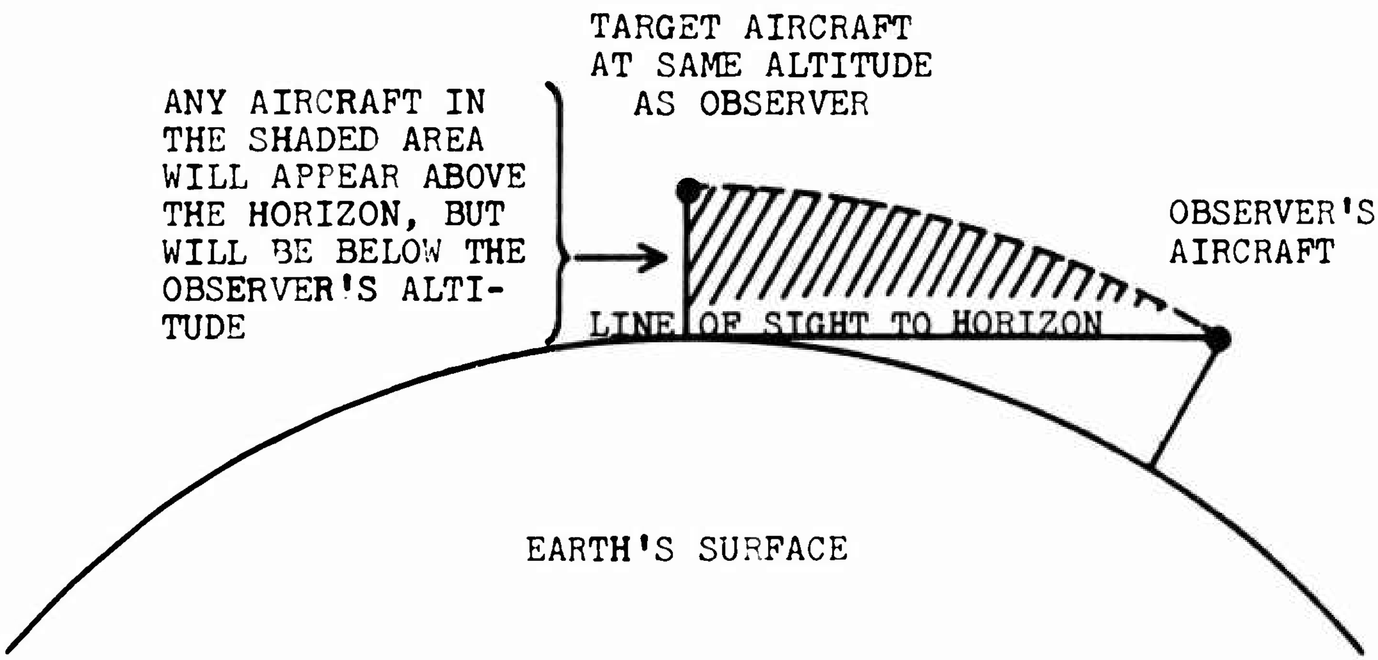

Fig. 5. Schematic diagram of the error which can occur in using the horizon rule to determine whether another aircraft is at the observer's altitude.

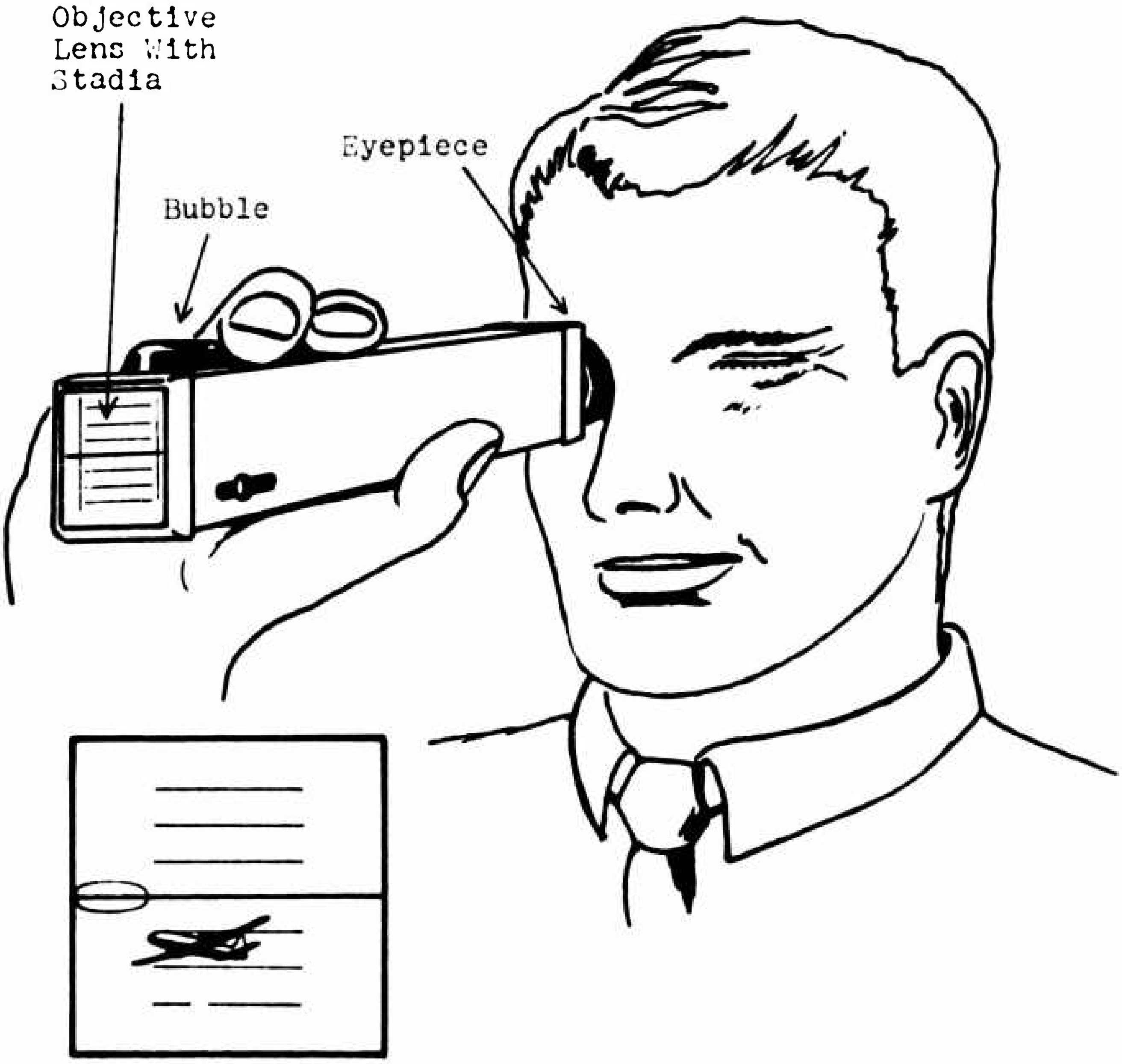

Fig. 6. A sighting level in use, and the view seen in making judgments of relative altitude.

distant and seen two stadia lines below center would be approximately 1,000 feet below the pilot.

Sighting levels appear to be useful as a backup to the horizon rule-of-thumb, or when the horizon is invisible, by providing a kind of artificial horizon. Lighting the stadia and bubble image would permit night use if the pilot were proficient in "two eyes open" sighting. In using a sighting level to accurately estimate altitude, the pilot must have knowledge of or be able to estimate the distance of other aircraft. Practically, however, the observer can aim the center line at the target and note whether the bubble lines up on the center line, or he can position the bubble on the center line and note where the target lies relative to the center line. In either case, the target is at the observer's altitude if it lines up with the center line.

Since the sighting level would be hand-held and therefore subject to hand tremor, instrument accuracies greater than one-fifth of a degree are probably not warranted, thus making even inexpensive sighting levels practical. However, a good sighting level should have: (a) a large, clear field of view, (b) some magnification probably not exceeding 4X, (c) a lighted objective, and (d) few stadia lines, probably not exceeding five, with each line representing 500 feet altitude separation at five miles.

Pilots experienced in the use of gunsights or bombsights, have suggested that collimated reticles be used to aid estimates of relative altitude and distance. At least one investigator (Brown, 1957) has studied the possibility of using collimated reticles to improve detection of other aircraft when the pilot is searching in a myopia-inducing homogeneous visual field.

The use of a collimated reticle as an optical aid is contingent on two major conditions: (a) it can be traversed horizontally across the normal field of view through an aircraft windshield, and (b) the line between the center of the reticle and a pilot's eye can be kept parallel to the ground. Constructed in this fashion, a collimated reticle really becomes a special case of a sighting level to estimate relative altitude. A collimated and calibrated reticle can also aid in estimating distance, provided the size of the sighted object is known or invariant. Unfortunately, this is not frequently the case; aircraft come in a variety of sizes, and often the type and size of aircraft cannot be identified until it is fairly close. As a consequence, since a small aircraft at five miles and a large aircraft at ten miles may subtend the same visual angle, the pilot is unable to differentiate the two. Size and speed are not invariantly related; hence, rate of increase in size would be difficult to use as a cue. Since the minimum information a pilot needs to avoid a collision is that the other aircraft is not at this altitude and/or on a converging course, there is questionable value in establishing a complex rule for estimating distances using a collimated reticle.

Pilots report extreme difficult in detecting other aircraft during high altitude flight. Numerous causes have been suggested: (a) anoxia, (b) glare, (c) windshield obscuration, (d) low contrast and small apparent size of distant aircraft, (e) narrow field of vision for objects at or near detection threshold, (f) difficulty of systematic search, and (g) an apparent myopia induced by a homogeneous distant visual field.

Whiteside (1957) in reporting studies of vision at high altitude emphasized that lack of detail in the distant visual field makes it difficult to keep the eyes focused at infinity. The myopia induced by such an "empty field" may range from .25 to 1.00 diopter (Whiteside, 1957; Luckiesh & Moss, 1940; Rees & Fry, 1941; O'Brien, 1953).

Collimated reticular patterns and lens, negative lens, and an accommodation stimulus mounted on the wing tip have all been proposed as techniques to overcome such induced myopia. In a laboratory study, Whiteside and Gronow (Whiteside, 1957) measured the minimum visual angle for recognizing a star-shaped pattern of small dots seen at optical infinity. In a completely empty field, the pattern was recognized (monocularly) when each dot subtended a visual angle of 0.81 minutes. When a collimated fixation pattern was superimposed, the minimal visual angle recognized averaged 0.43 minutes.

Brown (1957) used laboratory apparatus to simulate binocular search for aircraft against a bright, uniform background. The cues for near vision simulated an aircraft cockpit and windshield, while the cues for far vision were a pair of dots whose size and position could be varied. Under these conditions, the minimum size of target detected was measured using no reticle, a gunsight reticle, a circle of dots, and a checkerboard. Brown's results indicated that the collimated reticle did not significantly improve detection. Position of the target within the illuminated visual field did not affect its detection except that as distance from the center increased, the size of dot required for detection also increased. Subjects who had some degree of hyperopia were superior to normal or myopic subjects. These results indicate that collimated reticles have little or no value in aiding the detection of objects in an empty visual field.

REAR VIEW MIRRORS

Rear view mirrors, properly mounted to reduce aerodynamic drag and airframe vibration, could provide coverage of normally blind areas. Since they are free from optical aberrations and large light losses, require no focus adjustments, and permit a wide latitude of distances from the eye without affecting the field of view, mirrors produce a better image than most optical instruments. The geometry of mirror optics is simple and straightforward, thus the visual field is easily calculated. In order to cover the more important blind areas of large aircraft, several mirror systems may be required, each with its own problems of aerodynamic drag and airframe vibration.

Outboard and internal rear view mirrors have proven their value in automobiles. Convex mirrors, installed either internally or on front fenders, also have value, although the reflected images are less easily interpreted. As a consequence of a trend towards a lower roof in modern automobiles, the rear view mirror is, in some cases, placed all the way down onto the dashboard cowling, thereby restricting the rearward field of view. To give the driver of such vehicles full rearward vision, the American Optical Company (1959) has proposed a periscopic system installed in a false roof. Basically, the periscope consists of three optical elements: an objective lens which is cylindrical on one surface and flat on the other, a plane mirror to reflect the light down at a small angle, and a concave cylindrical mirror directing the light back toward the driver. Two versions of this installation are shown in Fig. 7. Such a system, mounted to keep vibration and aerodynamic drag to a minimum, could be a valuable aid in avoiding overtaking collisions. Feasibility has been demonstrated by the fact that a similar periscope with an objective lens only one inch high, providing a 30° vertical field, has been built for use in jet aircraft (American Optical Co., 1959).

Fiber optics may some day eliminate the need for light path channels and reflecting surfaces. Cylindrical glass fibers can be united into a flexible cable which will transmit a visual image from one end to the other, even around severe angles (see Fig. 8). At present, however, excellent resolution can be obtained only when fiber ends are in contact with an image on a plane surface. Little or no resolution occurs when objects are viewed at a distance. With further development of the state-of-the-art, fiber optics may have direct applicability as an optical aid covering areas normally blind to the pilot.

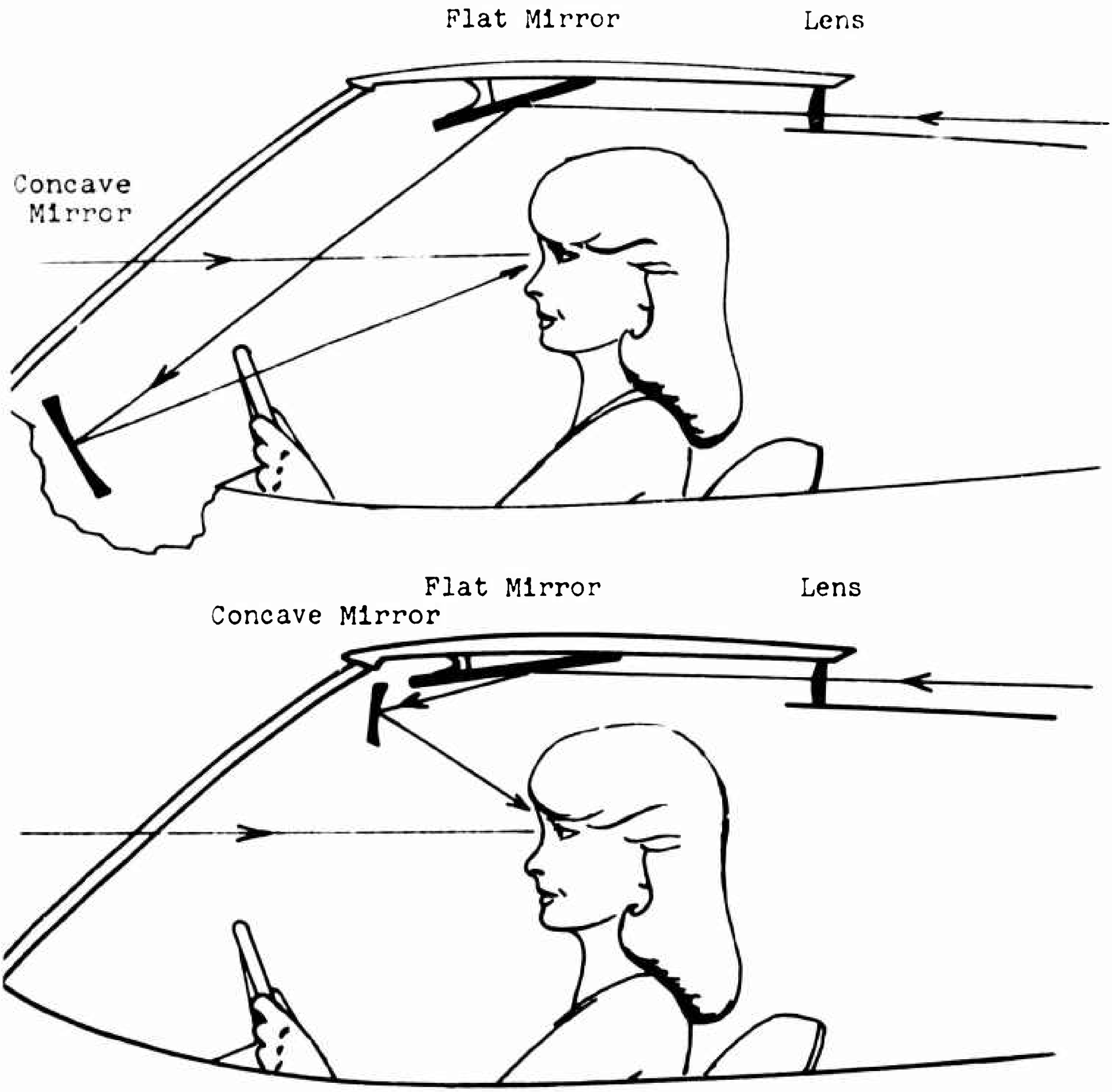

Fig. 7. Diagram of a periscopic system for rear vision from a vehicle. The bottom diagram illustrates the concave cylindrical viewing mirror mounted in a conventional rear-view mirror position. The top diagram shows the viewing mirror mounted on the dashboard where it does not obscure forward vision. (After American Optical Co., 1959.)

Fig. 8. A flexible "fiberscope" consisting of a bundle of 32,000 fibers mounted in a metallic sheath to prevent breakage. (From American Optical Co., 1960.)

Rear view mirrors have been tested on a Cessna 140 (Howell, 1958). Mirror vibration, caused by inadequate dampening of engine vibration transmitted through the airframe and/or by aerodynamic drag, destroyed their usefulness as optical aids. Aside from its annoying and fatiguing effect, vibration has been recognized as impairing visual performance. Research on the effects of vibration on visual performance has taken two directions: (a) the effects of vibration impressed on the body, and hence, the eyes, and (b) the effects of certain kinds of vibration in the visual field.

Coerman (1938) had subjects sit for two hours on a platform capable of oscillating through a frequency range of 15 to 1,000 cycles per second (cps). A decrement in subsequent binocular visual acuity of approximately 1.2 minutes of arc was found for vibration frequencies of 30 and 60 cps. In the 15 to 100 cps range, amplitudes exceeding 5 microns (.005 mm.) caused a decrement in visual performance. Vibrations greater than 140 cps had no effect on visual performance, apparently because the body absorbed these frequencies.

In a series of studies (Crook, Harker, Hoffman, & Kennedy, 1950), subjects performed simple mental arithmetic on printed numbers. The effect on the subjects' speed and accuracy was measured as vibration varied in frequency, amplitude, and form, and as the printed material varied in brightness, contrast, and type size. As far as relative vibratory movement was concerned, under high levels of illumination, reading printed numerical materials at 14 inches was not affected by amplitudes up to 0.02 inches, nor of dial markers up to 0.04 inches. However, under night illumination, the tolerances would be much less. If viewing mirror images is comparable to reading dial markers, then rear view mirror vibrations greater than 0.04 inches would tend to destroy their usefulness as an optical aid.

The above studies indicate that vibration, under certain conditions, degrades a pilot's visual efficiency. Additional research is needed, however, to determine the maximum amount of vibration that can be tolerated before a pilot's visual efficiency is degraded while using a given optical aid.

CLOSED-CIRCUIT TELEVISION

Closed-circuit television has been suggested by imaginative pilots and aircraft designers as a practical way of covering normally blind areas. From the cockpit designer's viewpoint, closed-circuit television gives him considerable flexibility in locating the camera and display tube with reference to each other. However, since a television system is electronic, both camera and display must be readily accessible for maintenance. This requirement tends to reduce the flexibility of location.

Because television images have poorer resolution and, at times, lower contrast ratios than purely optical images, detection and range judgments will be correspondingly degraded. Without an intense light source, resolution sufficient to provide a meaningful picture cannot be obtained at night. Also, at the present state-of-the-art, color cannot be economically provided as an additional cue. Equipping the camera with a "Zoomar" lens would give the pilot low magnification and large field for search, and higher magnification and smaller field for identification.

The "Electrocular," a device developed by Hughes Aircraft Company, possesses potential as a closed-circuit TV aid.[1] This device, shown in Fig. 9, provides a cathode ray tube image to one eye of the user without interfering with more distant vision by the same eye. The display tube weighs only [illegible] ounces; the entire head-mounted set only [illegible] ounces. The cathode ray tube image is reflected onto a transparent dichroic filter viewing eyepiece positioned 1 1/2 inches in front of one eye. The image can be adjusted so that at a distance of [illegible] feet it would appear to be 4 feet in diameter. The transparent eyepiece allows the viewer to monitor the TV image, or, by ignoring the image, to look through the eyepiece to more distant objects.

Closed-circuit television represents a relatively expensive way of covering normally blind areas to the rear. Generally, slower closing speeds are involved when one aircraft overtakes another. Extremes in detection range are not required for such situations, and a closed-circuit television system, even with its relatively low resolution, may adequately provide the pilot warning of overtaking aircraft.

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[1] Information on the Electrocular was provided by the Public Relations Department, Hughes Aircraft Company, Fullerton, California.

Fig. 9. The Hughes Electrocular display viewer.

The addition of a collimated reticle or similar sighting level type of device would allow the pilot to estimate the relative altitude of an aircraft to the rear and estimate whether it is overtaking or falling behind. If additional information is required, the pilot could, of course, maneuver his aircraft for direct visual inspection of the overtaking aircraft.

CONCLUSIONS

1. None of the optical aids which have been reviewed in this report can be recommended as providing the pilot with adequate assistance over the entire range of visual situations encountered in flight. Each aid has some practical value when used under a given set of conditions in a specific situation.

2. The most generally useful and immediately applicable optical aid for the pilot is a pair of sunglasses. Even though sunglasses reduce the distance at which other aircraft can possibly be detected, this is compensated for by the reduction of glare, lessened eyestrain, and generally increased comfort which may yield greater actual detection distances over extended flight. It is particularly important that pilots who fly at night protect their eyes during long exposure to high levels of brightness as the effects of such exposure are detrimental to night vision.

3. Sun visors are subject to a number of disadvantages, including poor optical quality, and are prone to become scratched and dirty. A head-mounted visor kept in a raised position above the eyes will protect the pilot from veiling glare; optical quality and cleanliness are, in this case, not as critical as when the visor is worn directly in front of the eyes.

4. Goggles tend to restrict the visual field and should be used only where the flight condition specifically requires protection of the eyes from wind, chemicals, or foreign objects.

5. No known optical aid can materially assist direct forward vision in searching for other aircraft. Once another aircraft has been detected, optical telescopes, either binocular or monocular, can be of value by increasing the distance at which a pilot can make relevant inferences about the other aircraft. They are of less value at high closing speeds and during severe buffeting.

6. Periscopes may be used to increase the pilot's visual coverage to the rear of his aircraft. However, they restrict the field of view, distort distance cues, and the objective lens must always be kept free of dirt, dust, oil films, and other light absorbing materials.

7. Sighting levels or collimated reticles may be used to aid in estimating the relative altitude of other aircraft.

8. Properly mounted rear view mirrors may provide some increased visual coverage to the rear. However, mirror vibration and vibrations acting upon the pilot degrade visual performance while using mirrors. Closed-circuit television, though feasible, is a more expensive method of providing vision to the rear.

RECOMMENDATIONS

The following recommendations appear to be justified on the basis of the literature and studies reviewed in this report:

1. All pilots should protect their eyes from high levels of illumination by means of a light filter. Gradient density sunglasses are desirable.

2. Aircraft owners should be encouraged to install rear view mirrors where it is structurally and aerodynamically feasible.

3. Pilots may find it useful to use sight levels with calibrated stadia lines to aid in judging the altitude of other aircraft relative to their own altitude. Simple, inexpensive devices acceptable (though not optimal) for daytime use are available.

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APPENDICES

A. Visual Space Perception and Detection

B. Effects of High Brightness

APPENDIX A

VISUAL SPACE PERCEPTION AND DETECTION

Sensitivity of the Eye

The human eye can respond over an intensity range of approximately 100 decibels, a ratio of ten billion to one, and can distinguish very fine spatial separations between portions of the visual field. Hecht and Mintz (1939) using a fine wire bisecting a lighter homogeneous visual field that subtended a large visual angle, found that the finest resolvable line at the highest illuminations subtended a visual angle of only 0.5 second. This is roughly one-sixtieth the width of a single foveal cone. In comparison, this acuity is 120 times greater than the "standard acuity" of one minute as measured by the Snellen Eye Chart.

Four primary factors limit visual acuity: (a) diffraction of light at the pupil, (b) aberrations of the eye, (c) size and density of the photoreceptors (rods and cones), and (d) ability of the nervous mechanism, from the receptor onward, to utilize differences in excitation. The first two are optical, the third anatomical, and the fourth neural. The neural limits are arrived at by assuming that small differences in the magnitude of stimulation are necessary to be reacted to by adjacent receptors. Then a visual acuity of 0.5 second of arc (as found by Hecht and Mintz, 1939) indicates that a difference of five per cent in the magnitude of stimulation of adjacent receptors is sufficient to elicit a perceptual response. Such a finding is close to theoretical limits imposed by the optical, neural, and anatomical limitations of the eye.

If contrast is above threshold, visual acuity increases as a function of illumination on the target. Data gathered by Koenig in 1897 are still applicable. They have been replotted by Hecht (1931) and are presented in Fig. A-1. Blackwell (1946) performed extensive research on the threshold of brightness contrast and found that as brightness increases, contrast threshold decreases (see Fig. A-2). In the region of small visual angles, he confirmed that the product of contrast and stimulus area required for 50 per cent detection is a constant (Riçco's Law).

A graphical plot of a hypothetical visual response (for example, visual acuity, contrast acuity, or brightness perception) as a function of the logarithm of increasing brightness is presented in Fig. A-3 (since it represents an idealization, no specific units are used). It will be noted that

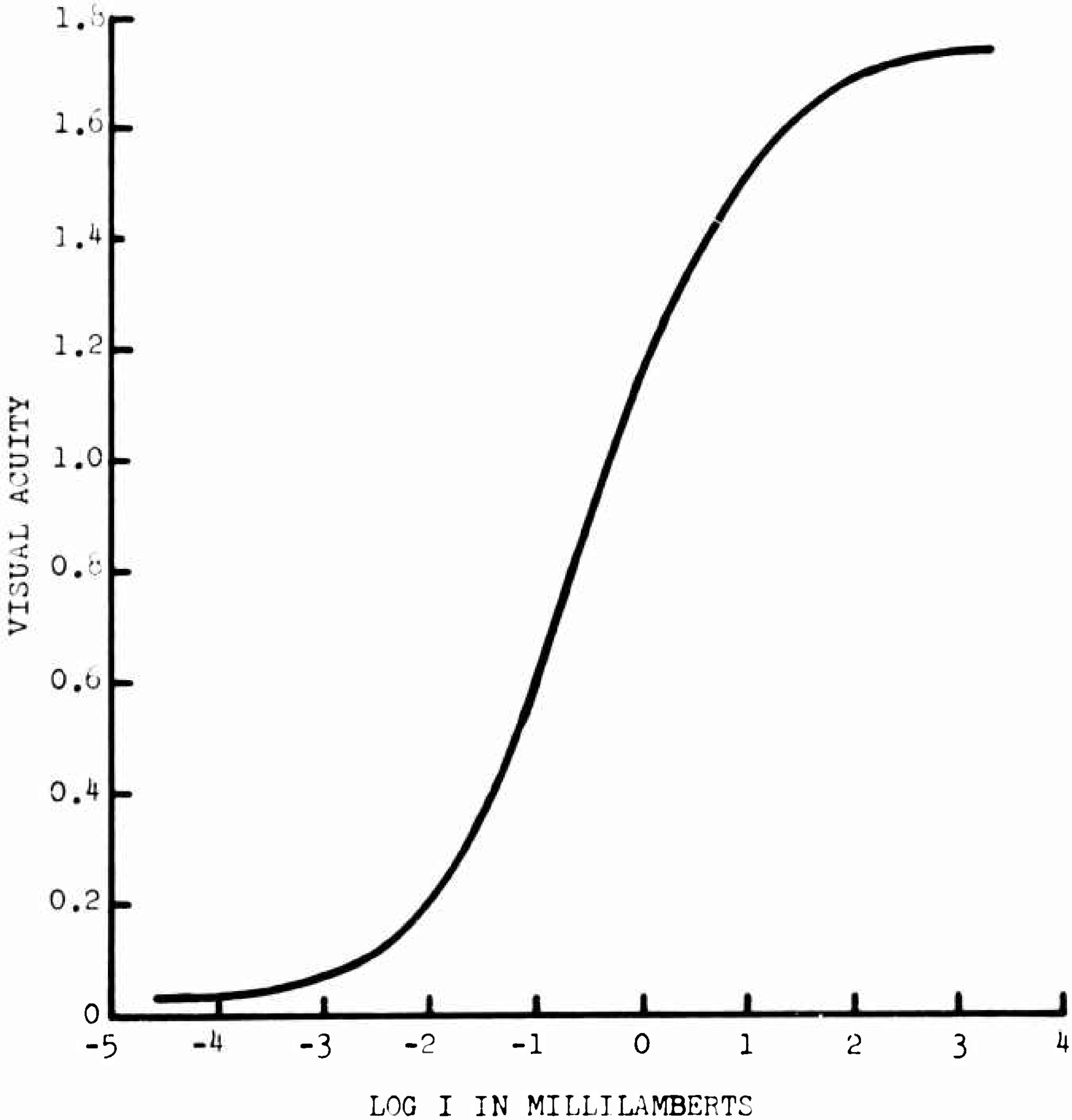

Fig. A-1. Visual acuity as a function of illumination intensity. (After Hecht, 1931, as presented in Geldard, 1953.)

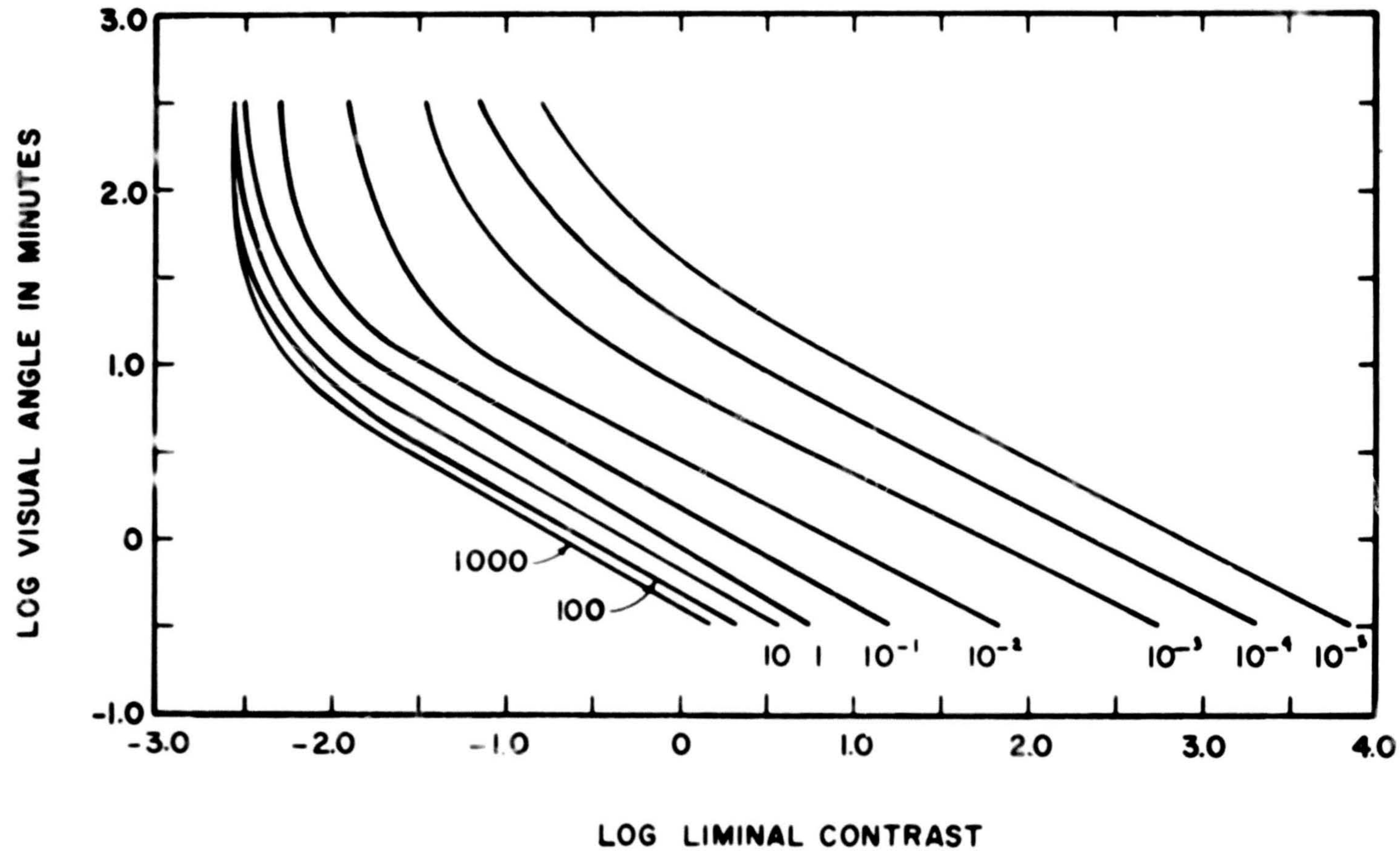

Fig. A-2. Relation between contrast threshold and area of target for several adaptation levels (intensity level of the field). (After Blackwell, 1946.)

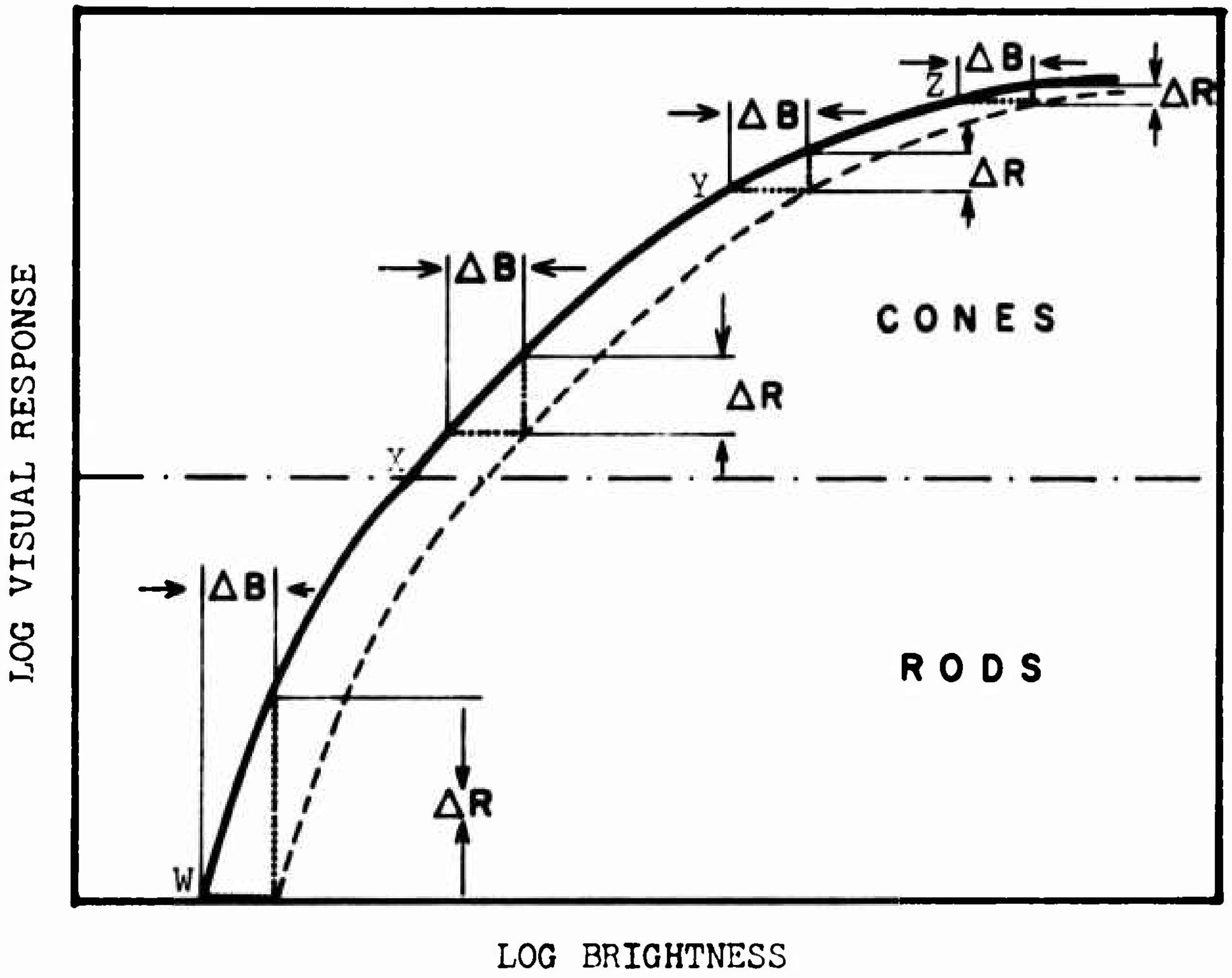

Fig. A-3. A hypothetical visual response curve as a function of brightness. (After Peckham & Harley, 1951.)

for a constant increment of brightness (ΔB), the increment of response (ΔR) decreases as the level of brightness increases; that is, ΔR is inversely related to brightness level. The point "W" represents the absolute threshold of vision; point "X" lies in the mesopic (twilight) region or slightly above the rod-cone transition; point "Y" represents normal reading illumination; point "Z" represents bright outdoor sunlight. Thus, the curves in Fig. A-3 indicate that reducing the level of illumination (for example, by wearing sunglasses) reduces the visual response, but that equal reductions in brightness yield quite different reductions in response depending upon the brightness before reduction. Thus, sunglasses worn at low levels of illumination produce a greater reduction in visual response than glasses worn at high levels of illumination.

The upper limit for brightness tolerance is generally considered to be around 16,000 millilamberts. Exposure to higher levels may cause severe pain or eye damage. At the other end of the continuum, one photon (the smallest unit of light energy) is theoretically sufficient to trigger a rod. Practically, however, the factors which determine the minimum light energy required to obtain a perceptual response in a fully dark-adapted eye are:

1. The diameter of the pupil (8 - 9 mm in fully dark-adapted eye);

2. The absorption, diffusion, refraction, and reflection of the aqueous and vitreous humors and other structures of the eye;

3. The probability that a photon will impinge upon a receptor capable of "firing"; and

4. The probability that sufficient receptors are stimulated in order to summate and produce a visual sensation.

Due to "losses" (difference between what enters the cornea and what reaches the retina), effective stimulation requires that a large number of photons strike the eye in order to trigger a perceptual response.

Visual Space Perception

Stimulus conditions for space perception are traditionally specified in terms of so-called cues, and these in turn, are divided into monocular and binocular cues. Monocular cues are those which can be perceived and used with a single eye. Binocular cues require the coordinated activity of both eyes.

The monocular cues are:

1. Relative size. Discrimination of distances is dependent on both retinal image size and past experience. Thus, a small retinal image of a familiar object like an automobile is interpreted as a distant automobile. Conversely, discrimination of size is dependent on the perceived distance (Gilinsky, 1951).

Size discrimination is also dependent on the number of additional cues available. When the stimulus conditions involve a maximum number of cues, size discrimination is in accord with expectations based on the law of size constancy (that is, familiar objects tend to be judged as of a certain size despite changes in their distance from the observer); when available cues are held to a minimum, size discrimination tends to follow the law of visual angle (in which the perceived size is that derived by the visual angle subtended by the object). To demonstrate this, Holway and Boring (1941) had subjects view stimuli while the field of view was restricted in various ways to reduce distance cues. In the most unrestricted condition, subjects viewed stimuli binocularly; in the most restricted condition, they viewed stimuli through a tunnel and artificial pupil that virtually reduced all distance cues. Subjects had to adjust the size of a comparison stimulus until it matched the stimuli they were viewing. The viewed stimuli were always one degree of arc in diameter regardless of distance. As shown in Fig. A-4, when viewed binocularly with all distance cues present, subjects tended to make the comparison stimulus larger as distance increased, which showed that their perception followed the law of size constancy. With virtually no distance cues present, subjects tended to follow the law of visual angle and make the comparison stimulus the same size regardless of the distance of the viewed stimulus.

These results indicate that pilots, in using telescopes or periscopes, will tend to make larger errors in size or distance estimations than they will with unaided vision. However, it is probable that training and experience with these aids would decrease such errors of estimation.

2. Aerial perspective. Distant objects undergo an apparent color change and tend to appear blue due to atmospheric scattering of light. In areas where the atmosphere is very clear (few suspended particles), the relatively small amount of scattered light may cause pilots unfamiliar with

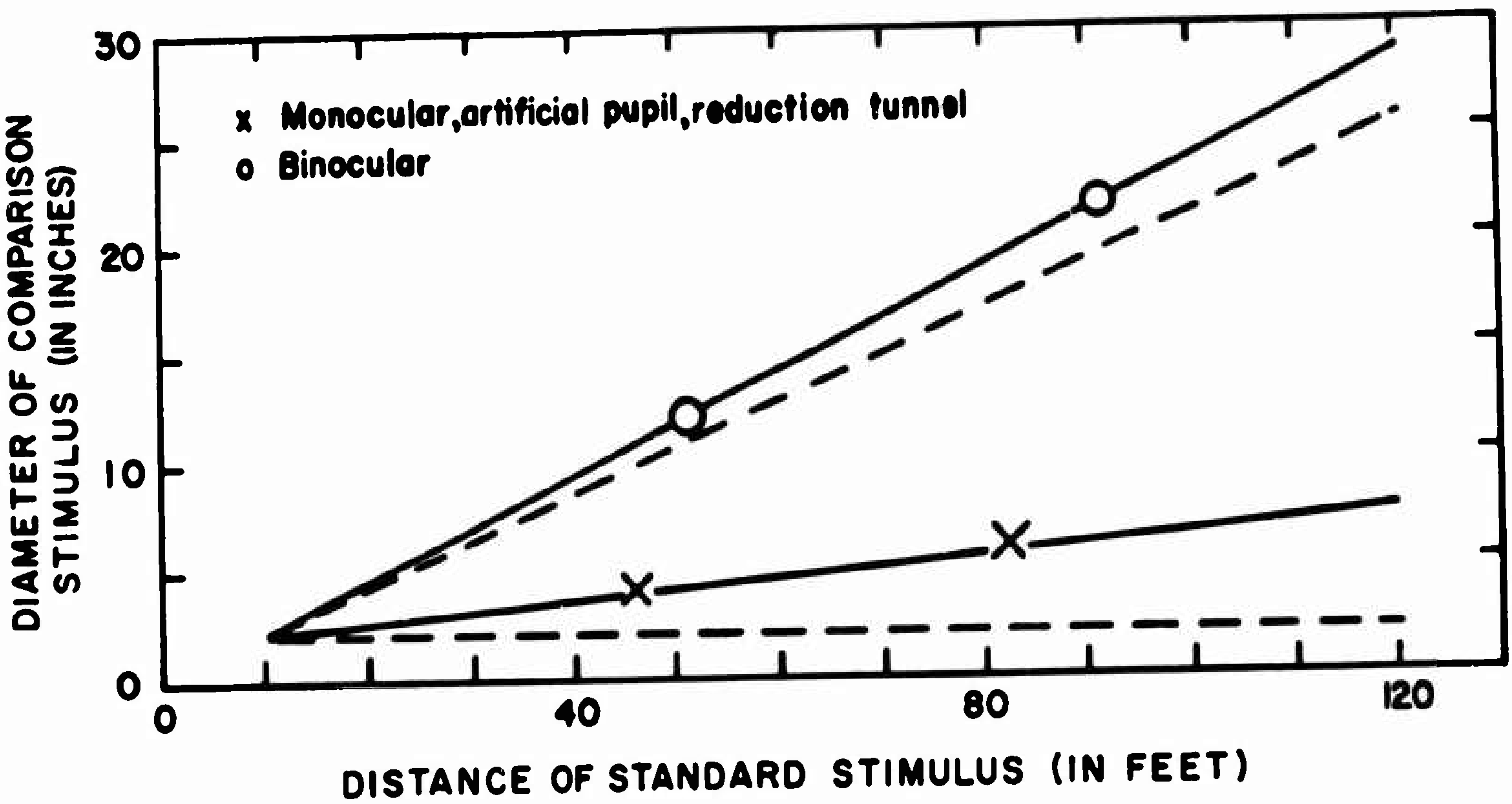

Fig. A-4. The effect of the presence or absence of cues on size discrimination. The inclined dashed line represents an expectation based on the law of size constancy; the horizontal dashed line represents expectation based on law of visual angle. (After Holway and Boring, 1941.)

this characteristic of clear atmospheres to underestimate the distance of far objects.

3. Brightness and color contrast. The ratio of the brightness of an object to the brightness of its surround may be expressed as:

$$C = \frac{B_o - B_s}{B_s}$$

where B_o and B_s are the brightnesses of the object and its surround, respectively, and C is the brightness contrast. When the object is darker than its surround, brightness contrast is negative and ranges from 0 to -1; when the object is lighter than the surround, contrast is positive and ranges from zero to infinity. Positive contrasts greater than two to five will seldom be experienced during daylight flight.

Both color and brightness contrast of an object decrease as its distance from an observer increases. The loss in brightness contrast is due to the addition of scattered light in dark areas of the distant object; the loss in color contrast is due to atmospheric absorption of the wavelength characteristic of the color. Because of its rapid attenuation, reflected color is seldom a valuable distance cue beyond three to four miles.

4. Linear perspective. As parallel lines (for example, railroad tracks) recede from an observer, they subtend a smaller and smaller angle at the eye and, thus, appear to converge.

5. Interposition. Objects nearer to the observer will partially block and overlap more distant objects. This provides a relative distance cue. The retinal images of nearer objects will be interposed over those of farther objects and hence they will be judged as nearer.

6. Texture gradient. Surfaces which display a texture or pattern and extend into the distance (for example, a plowed field or brick roadway) are seen as slowly changing from a surface of discrete units near at hand to a homogeneous surface in the distance.

7. Accommodation. When the eye is fixated on an object in space, the object and other objects slightly nearer or farther away are sharply focused on the retina while all other objects are blurred. The discrimination of the clearly focused image from the blurred images serves as a distance cue, but is limited to a very few feet.

8. Movement parallax. When a viewed object moves with respect to an observer's eyes, or vice versa, a differential angular velocity exists between the line of sight to a fixated object and that to any other object in the visual field. Near objects move against the direction of movement, while far objects move with the direction of movement.

Binocular cues for space perception are:

1. Convergence. When very distant objects are fixated, the lines of fixation for the two eyes are parallel. When near objects are fixated, the eyes are turned in a coordinated manner so that the lines of fixation converge on the object. Slight convergence indicates the object is distant; large convergence indicates the object is near. Convergence cues are not, however, effective beyond 60 feet, and in most cases, effectiveness is limited to a yard or so.

2. Stereoscopic vision. Due to the separation of the eyes, the retinal image of an object is slightly different for each of the two eyes. Fusion of the two retinal images results in the perception of depth. The depth effect can be exaggerated or lessened by increasing or reducing respectively the interocular distance. This is sometimes done with optical devices such as range finders. Without such artificial exaggeration, depth perception based on retinal disparity is normally limited to about 60 feet.

Detection

A pilot, in visually monitoring the surrounding airspace to avoid possible collisions, must search for, detect, and identify hazardous objects. Search, involving scanning of a large field of view, depends primarily on such factors as: (a) search habits, (b) head and eye movements, (c) saccadic eye movements--the number and distribution of fixation points, (d) level of accommodation, and (e) level of illumination. Detection, involving primarily visual acuity, depends on (a) level of accommodation, (b) depth of visual field, (c) level of light adaptation, (d) threshold for contrast, (e) size and distance of object, (f) mental and physical state, (g) experience with a given class of objects, and (h) location of the target relative to the observer. Identification is a complex process involving most, if not all, of the cues of space perception as well as recognition of the relevant and significant characteristics of an object.

The above list of determinants of visual target detection is representative, not exhaustive. The determinants which affect the various aspects of detection are many and varied. For example, Kulp and Rowland (1959) cite 476 studies pertaining to the general problem of daylight visual target detection. However, they may be roughly grouped into three broad categories: (a) human characteristics, (b) stimulus characteristics, and (c) characteristics of the environment.

Basically, detection is the discrimination of a difference or of a change. Discrimination of a difference may be illustrated by the comparison of the size of one object with respect to another or the presence or absence of an aircraft in the sky. Discrimination of a change may be illustrated when increasing size is interpreted as an approaching aircraft or when a change in position as a function of time is interpreted as movement.

Other factors being constant, detection threshold[1] will vary as a function of the visual acuity of the pilot and as a function of the size, distance, and, to some extent, form of the object. Hyperopic and normal vision pilots can detect objects farther away than myopic ones. However, hyperopic pilots (who see distant objects with less eye muscle strain than near ones) cannot see farther or more clearly at a given distance than those with normal vision.

If size and contrast of a stimulus are above threshold, the likelihood of detection will increase as contrast increases. This relationship is linear for visual angles less than one minute of arc, and curvilinear for larger visual angles. An object possessing the quality of color may be detected because of color contrast alone or because of both color and brightness contrast. Objects exhibiting high positive contrast ratios may be detected at greater distances than those of negative contrast, because (a) brightness contrast ratios greater than +1 can be obtained while negative ratios are limited to -1, and (b) the addition of scattered light to the dark areas of distant objects decreases negative contrast ratios (Middleton, 1958). Duntley (1948) has compiled a series of nomographs which show the detection range for circular objects of various size and contrasts under different levels of illumination and meteorological range.

The probability of detecting distant objects when the eye is focused for near objects is considerably poorer than when it is focused for far objects. When the eye is focused

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1 Detection threshold is defined statistically as that difference or change which is just detectable 50 per cent of the time.

for a given distance, objects slightly closer or farther away will also be in focus; all others will be out of focus. Objects out of focus may still be detected if they have high attention-getting powers. For example, an intense light or a moving object may be seen in peripheral areas of the eye. Since detection threshold is a function of visual acuity, it is also a function of level of illumination. In addition, any change in the level of adaptation to a given level of illumination may seriously affect detection threshold. Brief exposure to glare will increase detection threshold of the dark-adapted eye for a considerable period of time.

Thus, the detection threshold is a function of many variables interacting in various and diverse ways. Except in a laboratory where the many variables can be controlled or specified, prediction of whether an object will or will not be detected is extremely difficult.

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APPENDIX B

EFFECTS OF HIGH BRIGHTNESS

Brightness and Photopic Vision

The effects on photopic vision of prolonged exposure to excessively bright light have received scant attention. In a series of studies, Peckham and Harley (1951) investigated the effects of 10 to 12 hours exposure to ocean-front sunlight with brightness levels from 8,000 to 20,000 millilamberts. The subjects (beach guards) were divided into three groups: one group wore no sunglasses, one wore sunglasses with 35-50 per cent transmission, and one wore sunglasses with 10-12 per cent transmission. Visual performance was measured by means of the critical flicker frequency (CFF) technique.

The results indicated that visual sensitivity measured by CFF performance decreased as a function of prolonged exposure to excessive sunlight. For subjects without sunglasses and those who wore sunglasses of medium density, a daily decrement occurred. Only partial recovery of the day's loss occurred overnight, and the net loss was cumulative over a week. In contrast, the subjects who wore dark sunglasses consistently improved during the week. On the average, the group not wearing sunglasses exhibited a daily decrement of 50 per cent when compared with the dense sunglass group.

Peckham and Arner (1952) studied senior college students at Arizona State College who drove automobiles for a period of four and one-half to seven hours per day. The average illuminance ranged from 475 to 750 footlamberts as measured at the driver's eyes. Critical flicker frequency and visual acuity measurements were taken at the end of the day's run. Visual acuity was measured using nine equal-sized circles filled with cross-hatching (the squares being 4.22, 3.55, 2.98, 2.50, 2.11, 1.77, 1.49, 1.26, 1.05, and 0.89 mm. in width, and at 20 feet representing a Snellen range of 20/48 to 20/10). The circles were presented at three contrasts (.92, .53, .33), two luminous reflectances (1.0 footlambert, 0.1 footlambert), and two distances (10 and 20 feet).

The results of the visual acuity measurements indicated no daily variation when the stimulus luminous reflectance was 1.0 footlambert. At low stimulus brightness (0.1 footlambert), there was a slight daily decrement for stimuli of low contrast values (.53, .33). Visual performance, as indicated by CFF, showed consistent, daily decrements. Contrary to the previous study (Peckham & Harley, 1951), no cumulative effect was exhibited over the course of the experiment, perhaps because illumination levels were relatively lower.

The above studies indicate that photopic visual performance as measured by CFF is affected by prolonged exposure and that the effect is cumulative. Whether photopic visual acuity is affected remains unanswered; the effect, if any, may be of short duration and affect only stimuli of low contrast. The data suggest that for low contrast stimuli, the greater the difference between exposure brightness and test brightness, the greater the decrement in visual acuity. Prolonged exposure to high levels of brightness will result in eye strain and tearfulness, thus reducing over-all visual efficiency.

Taking into consideration only the effect of contrast upon detection threshold, it would seem reasonable to expect a pilot to experience increasing difficulty in detecting intruder aircraft of low contrast value the longer he flew in bright sunlight. If he is flying above cloud cover and suddenly drops down through it during his landing approach, his detection threshold for low contrast stimuli may increase.

Brightness and Scotopic Vision

Because it is extremely important to military night operations and to automobile and aircraft safety, the effects on scotopic (night) vision of exposure to bright light have received considerable attention. Hecht, Hendley, Ross, & Richmond (1945) light-adapted subjects by having them look at the sky for from two minutes to five hours. Sky brightness varied from 3,000 to 16,000 millilamberts (short exposure times were used at high intensities due to eye discomfort). After exposure, subjects were dark-adapted and tested on the Hecht-Shlaer Adaptometer using blue light.

The results indicated that exposures to ordinary sunlight produced both temporary and cumulative effects on scotopic vision. A single exposure of two to three hours delayed the onset of dark adaptation by ten minutes or more and slowed the process itself so that the normal scotopic vision threshold was not reached for several hours. Figure B-1 shows the significant parts of four representative dark adaptation curves for one subject. Since the measurements were made on different days, the curves were adjusted so that the initial threshold before light adaptation was the same for each day. After 60 minutes of light adaptation to 50 millilamberts, recovery is complete after 40 minutes in the dark, while even a two-minute exposure to 7,000 millilamberts prolongs the recovery time to about an hour.

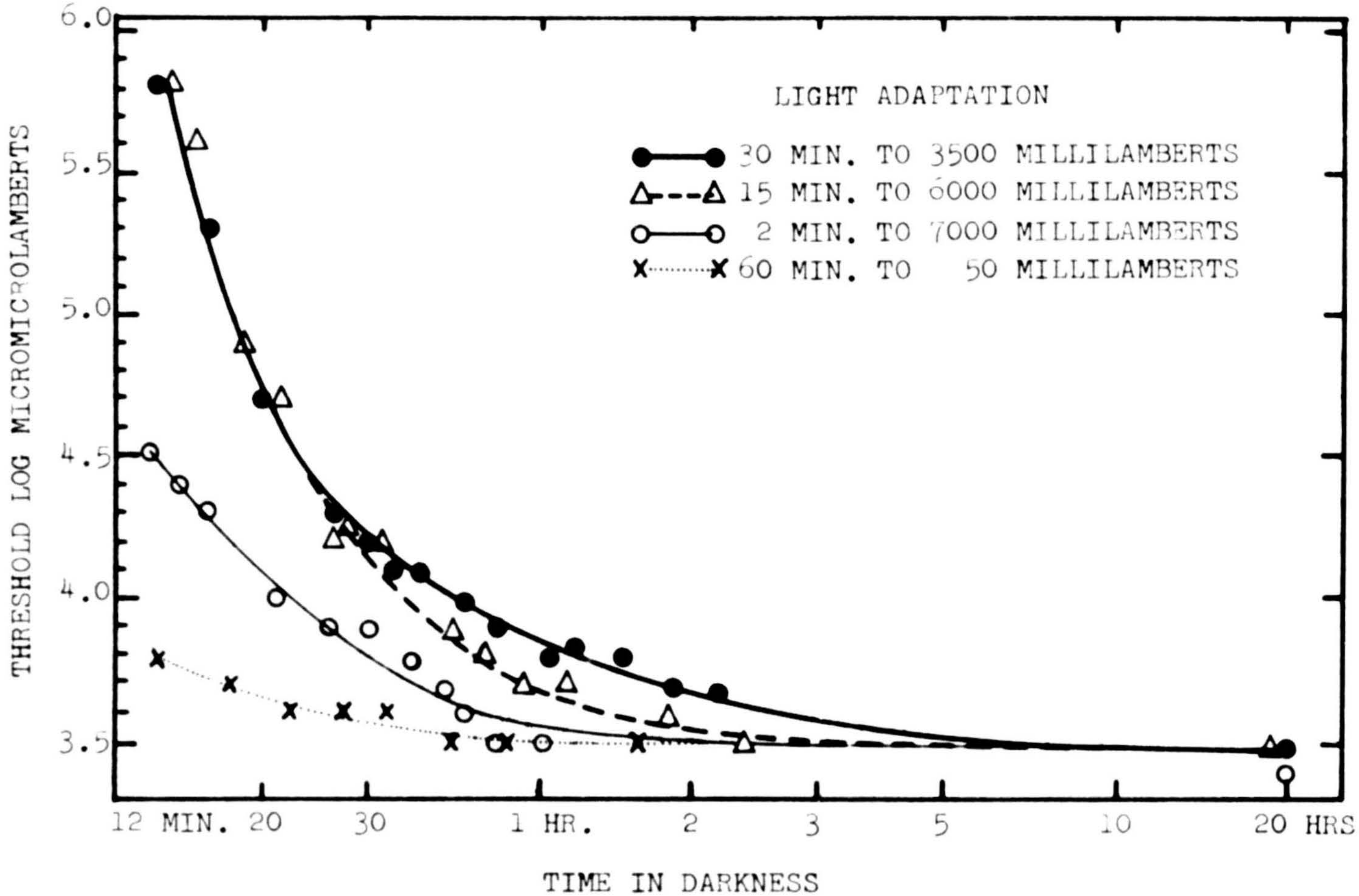

Fig. B-1. Time required to dark adapt after various exposures to bright sky. (After Hecht et al., 1945.)

Figure B-2 represents the scotopic vision thresholds for a group exposed to outdoor bright sunlight and a control group whose members wore red goggles whenever they went outdoors. The two groups were selected as having almost identical thresholds. During the last few days of the study, the two groups exchanged conditions. After repeated daily exposures to sunlight, the delay in reaching the normal scotopic vision threshold persisted overnight. The night vision threshold after complete dark adaptation increased each day for about ten days, then lowered slightly and remained at the same level. Although there was considerable individual variation, on the average, the dark adaptation thresholds rose by about 0.2 log units, corresponding to a loss of about 50 per cent in scotopic visual acuity, range of visibility, contrast discrimination, and frequency of sighting a just-detectable target. Figure B-3 demonstrates graphically how a rise of 0.2 log unit affects night visual performance. The rise shifts the whole curve by 0.2 log unit, as indicated by the dotted line in Fig. B-3. Thus, if a normal pilot can detect an airplane nine times out of ten, a pilot who has been exposed to strong sunlight will detect the same target under the same conditions only four or five times out of ten.

A seasonal variation in scotopic sensitivity has been reported by Sweeney, Kinney, & Ryan (1960), who found that scotopic sensitivity was best in winter and early spring, and poorest in summer and early fall. Figure B-4 presents the curve of scotopic sensitivity averaged for each month of the year. The test units are arbitrary numbers assigned to lights varying in size (from 0.07 to 0.34 degrees visual angle) but remaining constant in intensity (approximately 5.0 log micromicrolamberts). They found a high negative correlation (-.79) between the amount of blue light reflected from the skin and scotopic sensitivity; that is, white skin indicated lack of exposure to strong sunlight and hence better scotopic sensitivity.

In summary, exposure to high levels of illumination not only increases the time required to complete dark adaptation but also increases the absolute threshold of scotopic vision. Further, these effects are cumulative over a period of time.

Glare

One of the most ubiquitous and annoying problems in flying is the existence of glare. This highly complex phenomenon occurs under many different conditions, in many different forms, and with a wide variety of effects. The pilot may be subjected to glare from above, below, or from either side, during either day or night, and either directly or by reflection. He may be exposed continuously to glare (flying into

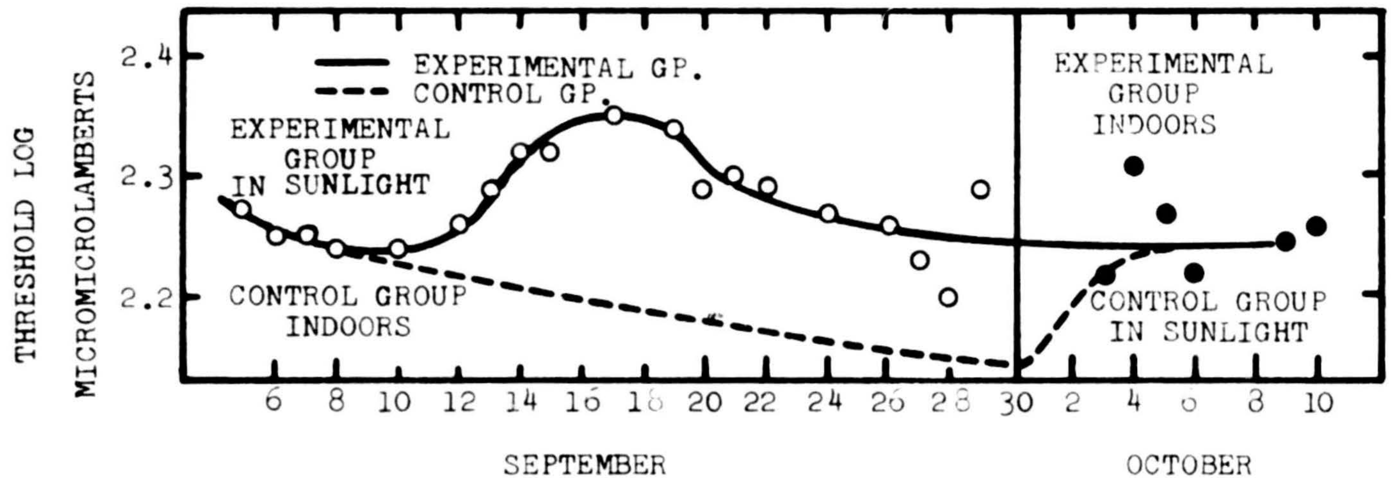

Fig. B-2. Effect of sunlight on scotopic threshold. (After Hecht et al., 1945.)

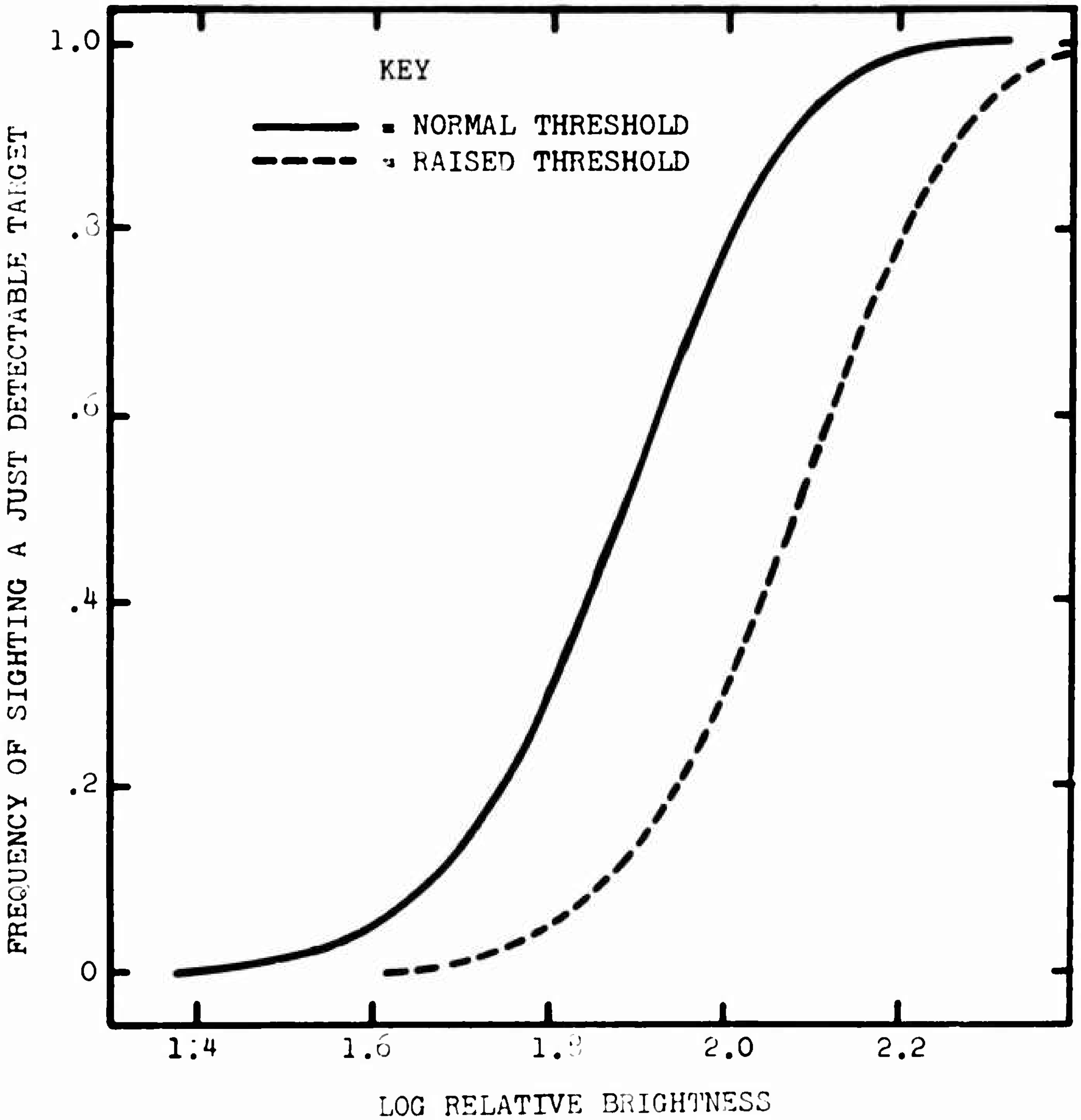

Fig. B-3. Effect of raising threshold 0.2 log unit on frequency of sighting a target just detectable. At any brightness level, the probability of detecting the target is lower for the raised threshold. (After Hecht et al., 1945.)

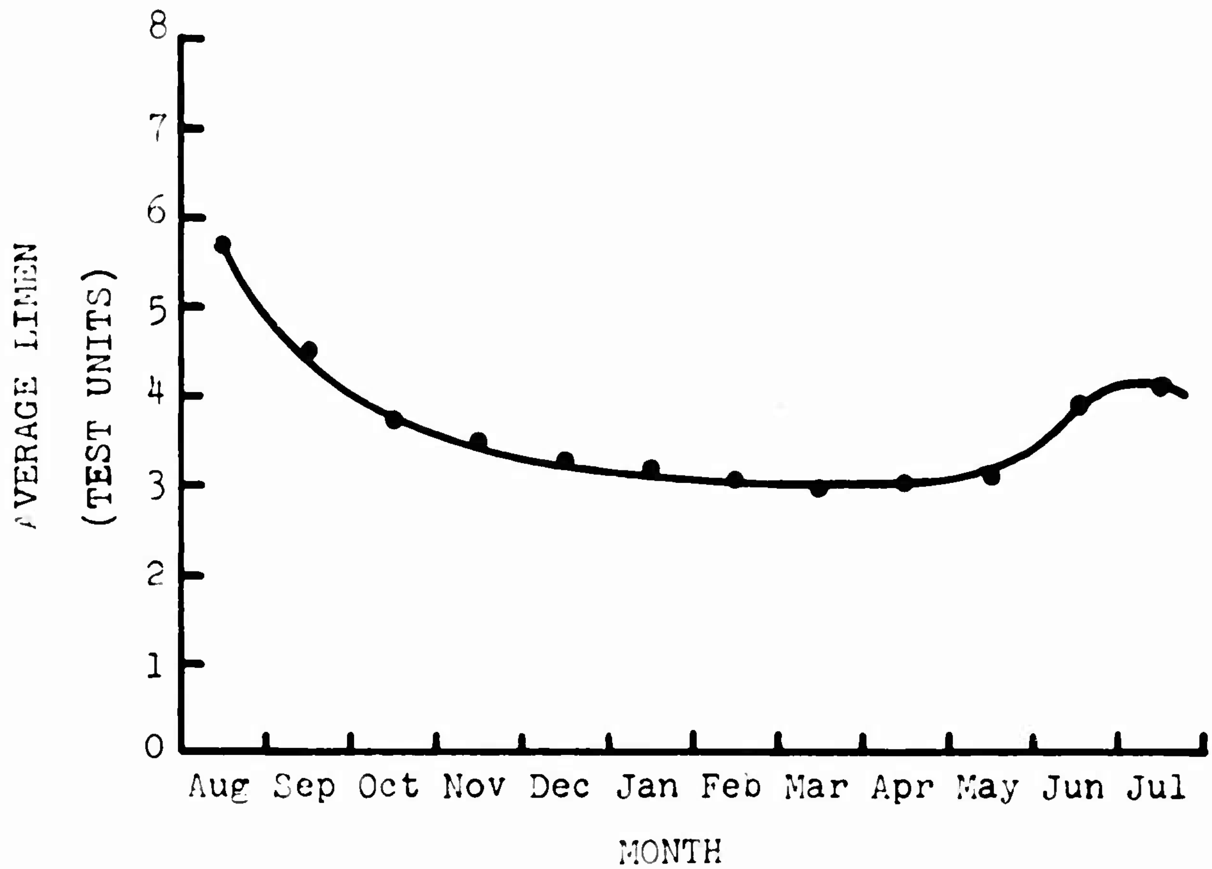

Fig. B-4. Scotopic sensitivity as a function of time of year. (After Sweeney et al., 1960.)

the sun), momentarily (lightning flash), or intermittently (anti-collision light). Glare may be of high or low intensity. It may affect vision during or after its occurrence or both, and can seriously affect the level of dark adaptation for a considerable time after its cessation.

Glare has been defined in many ways. For example, it has been defined in terms of the conditions under which it occurs, its form and physical properties, and its effects on vision. Generally, glare is considered as any amount of light falling upon the retina in excess of that which enables one to see clearly. It can be differentiated into:

1. Veiling glare caused by light which is uniformly distributed over the whole retina or superimposed over the whole retinal image;

2. Dazzle glare caused by adventitious light which is scattered over the whole retina; and

3. Scotomatic (blinding) glare caused by light of sufficient intensity to reduce retinal sensitivity in whole or in part. Two kinds of scotomatic glare may be differentiated: (a) that in which retinal sensitivity is reduced during and after exposure, and (b) that in which retinal sensitivity is affected only after return to a lower level of illumination.[1]

The major distinctions between veiling and dazzle glare are (a) uniformity versus nonuniformity of the distribution of light on the retina, and (b) complete versus partial coverage of the retinal image. Their effect on vision also differs; veiling glare reduces contrast while dazzle glare confuses the eye by disrupting the contours of the retinal image. Both types affect visual performance only during the occurrence of glare. Scotomatic glare, on the other hand, reduces retinal sensitivity during and after cessation of glare. If the duration of scotomatic glare is prolonged, the effect is a rise in the level of adaptation; if the duration is short, an afterimage is formed.

Veiling glare is the commonest type found in flying (Whiteside, 1957). Fortunately, it is the easiest to deal with, since to overcome it one needs only to shield the eyes with the hand or a visor. Dazzle and scotomatic glare, however, require that luminosity of the visual field be reduced,

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1 After Bell, Troland, & Verhoeff, 1922.

usually by means of a filter. In the case of high intensity, all three types of glare are present.

The visual image produced by scotomatic glare is a prolongation of the physiological processes involved after cessation of the stimulus. Essentially, an afterimage is a temporary, relatively blind area (intense stimuli can still be seen) or scotoma. Duration and intensity of the scotoma are proportional to the duration and intensity of the original stimulation. Fry and Alpern (1951) indicate that retinal re-adaptation after exposure to moderate intensities of light follows a definite pattern; with short exposures, intensity times duration is a constant ($I \times T = K$).

Ordinarily, after exposure to glare there is a continued sensation of light for a short period (due to receptor/neural lag) followed by an alternating series of positive (similar brightness) and negative (opposite brightness) afterimages. If glare is of sufficient duration and intensity, the afterimages will reduce or entirely obliterate foveal (area of highest visual resolution) perception until they dissipate. Thus, as the degree of scotoma increases, the luminance of a stimulus must also be increased in order to be perceived.

Under conditions of glare, the normal pupil constricts, thereby reducing the light reaching the retina (Reeves, 1920; Luckiesh & Moss, 1934). The light reaching the photoreceptors alters the adaptation state of the retinal region on which the image of the glare-source falls (Ferree, Rand, & Harris, 1933; Moon & Spencer, 1943 & 1945). Adjacent retinal regions undergo changes in adaptation state which have been ascribed to retinal (neural) interaction (Fry & Bartley, 1955), but are probably caused largely (perhaps entirely) by the action of stray light (Fry, 1954). The scatter of light is due to diffuse transmission of light through the sclera and iris and to flares produced at various refractive surfaces, specular reflections, fluorescence of the lens, and scatter within the ocular media owing to the inhomogeneities in structure (Duke-Elder, 1938). Earlier studies did not explain glare as a function of scatter because transmission of the ocular media had been assumed too high (Stiles, 1929). Later measurements of transmission permitted higher absorption and greater scatter to be assumed (Ludvigh & McCarthy, 1938).[1]

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[1] The summary of effects of glare presented in this paragraph is extracted from Wolf's (1960) study of effects of glare as a function of age.

The visibility of test targets in the vicinity of a glare was found by Wolf and Zigler (1959) to be dependent upon (a) the size and luminance of the glare source, (b) the angular separation between glare source and target, (c) the size and luminance of the target, (d) the exposure duration, and (e) retinal location. Regardless of test field size and/or retinal location, visibility thresholds became lower as the angular separation between glare field and test field was increased, and as exposure duration increased. When exposure durations were greater than one second, or were continuous, visibility thresholds increased. The thresholds also increased if size and/or luminance of glare field was increased. Thresholds were found to be lower when fixation was at the edge of the test field rather than at the edge of the glare field. However, when the test field was large, the thresholds were the same, regardless of fixation point.

The effect of glare on subsequent vision varies with individuals. Some pilots complain of the discomfort produced by glare, while others flying under identical conditions apparently experience little or no discomfort. DeSilva & Robinson (1938), in an investigation of glare produced by headlights at night, divided 1200 subjects into those with light irises and those with dark irises (irrespective of color). They found that those with light irises were unable to perform as well in the presence of dazzle glare as did those with dark irises, presumably because a dark iris transmits less light.

Changes in visual functions with age have been found by a number of investigators (Simonson, Enzer, & Blankstein, 1941; Brozek & Keys, 1945; Misiak, 1947; McFarland & Fisher, 1955; Wolf, 1960). Wolf (1960) investigated the effect of scotomatic glare on the ability to see gaps in Landolt C's presented at angular distances of 4, 7, and 10 degrees from a glare source. Subjects ranged in age from 5 to 85 years. As the glare luminance was increased from 1 to 15,000 millilamberts, the luminance of the target screen on which the Landolt C's were presented had to be increased proportionately. Comparing individuals in the 5 to 15 year-old group with those in the 75-85 group, a 50- to 70-fold increase was found in target screen luminance required. At the age of 40, there was a sudden acceleration in sensitivity to glare (see Fig. B-5). Studies of patients with incipient and extracted cataracts suggest that opacities of the lens and the resulting entoptic scatter of light may be primarily responsible for the phenomenon of dazzle glare.

The rate at which the eye becomes dark-adapted is important for nighttime flying. Rate of adaptation is a function of several conditions, including duration, intensity, and

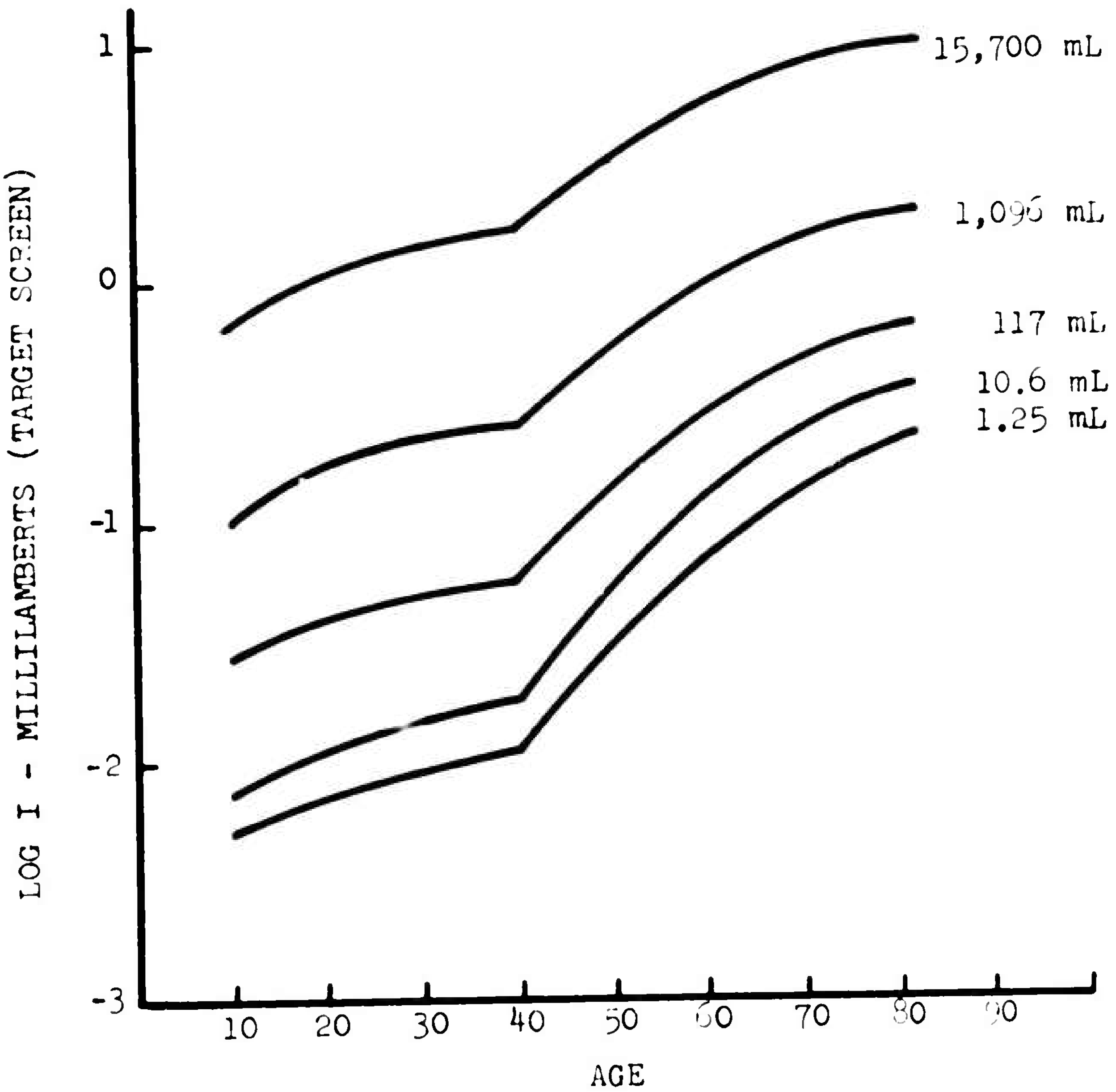

Fig. B-5. Relation of target recognition thresholds to glare luminances at several ages. (After Wolf, 1960.)

wavelength of the light the individual has been exposed to before start of adaptation. Figure B-6 presents the dark adaptation recovery times after exposure to four different brightnesses of white light. Figure B-7 shows the course of dark adaptation after the eye has been exposed to lights of different colors.

In turn, the above conditions vary as a function of altitude, atmospheric conditions, time of day, time of year, and even geographic area. Figure B-8 illustrates that age has little effect on rate of adaptation, but does yield a decrease in level of dark adaptation.

In summary, considerable research has been done on the effect on vision of brief exposures to bright light (glare), especially in night driving. Such exposures increase the levels of adaptation. Since recovery time of the cones is roughly two to three minutes, the effect produced by exposure to glare is relatively brief and hence does not seriously affect photopic vision. The relatively long recovery time of the rods after exposure to a bright light is, however, a serious factor.

Veiling glare, the commonest type found in flying, is the easiest to deal with, requiring merely that the eyes be shielded. Under photopic conditions, some type of filter can effectively reduce the adverse effects of glare. Unfortunately, even a 30 per cent transmission filter seriously reduces visibility under mesopic and scotopic luminance levels, a problem for which no practical solution has yet been found.

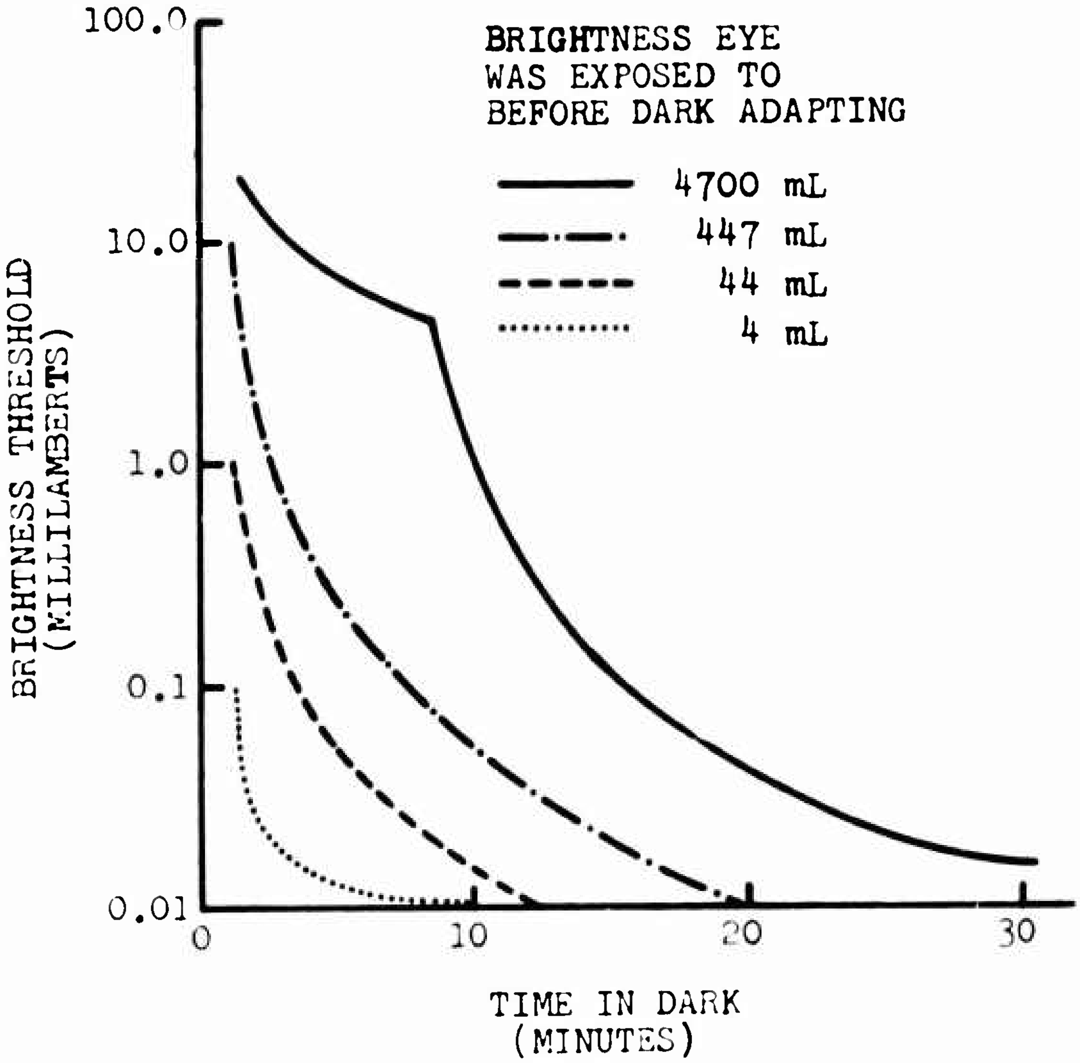

Fig. B-6. Time to recover dark adaptation after exposure to a white light at four different intensities. (Data from Haig, 1941, as reproduced in Morgan, Cook, Chapanis, & Lund, 1963.)

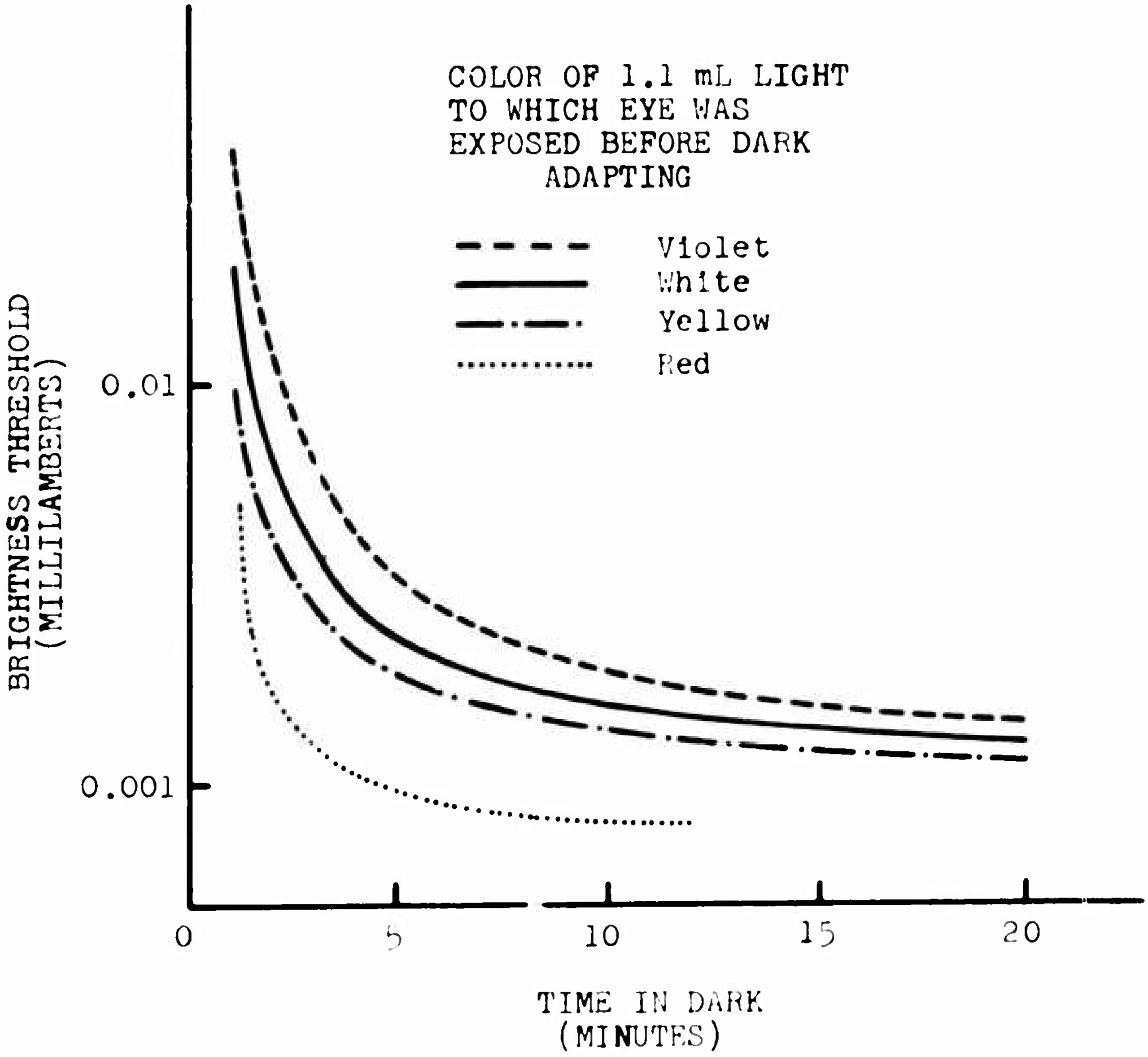

Fig. B-7. Time to recover dark adaptation after exposure to lights of different colors. (Data from Peskin and Bjornstad, 1948, as reproduced in Morgan, Cook. Chapanis, & Lund, 1963.)

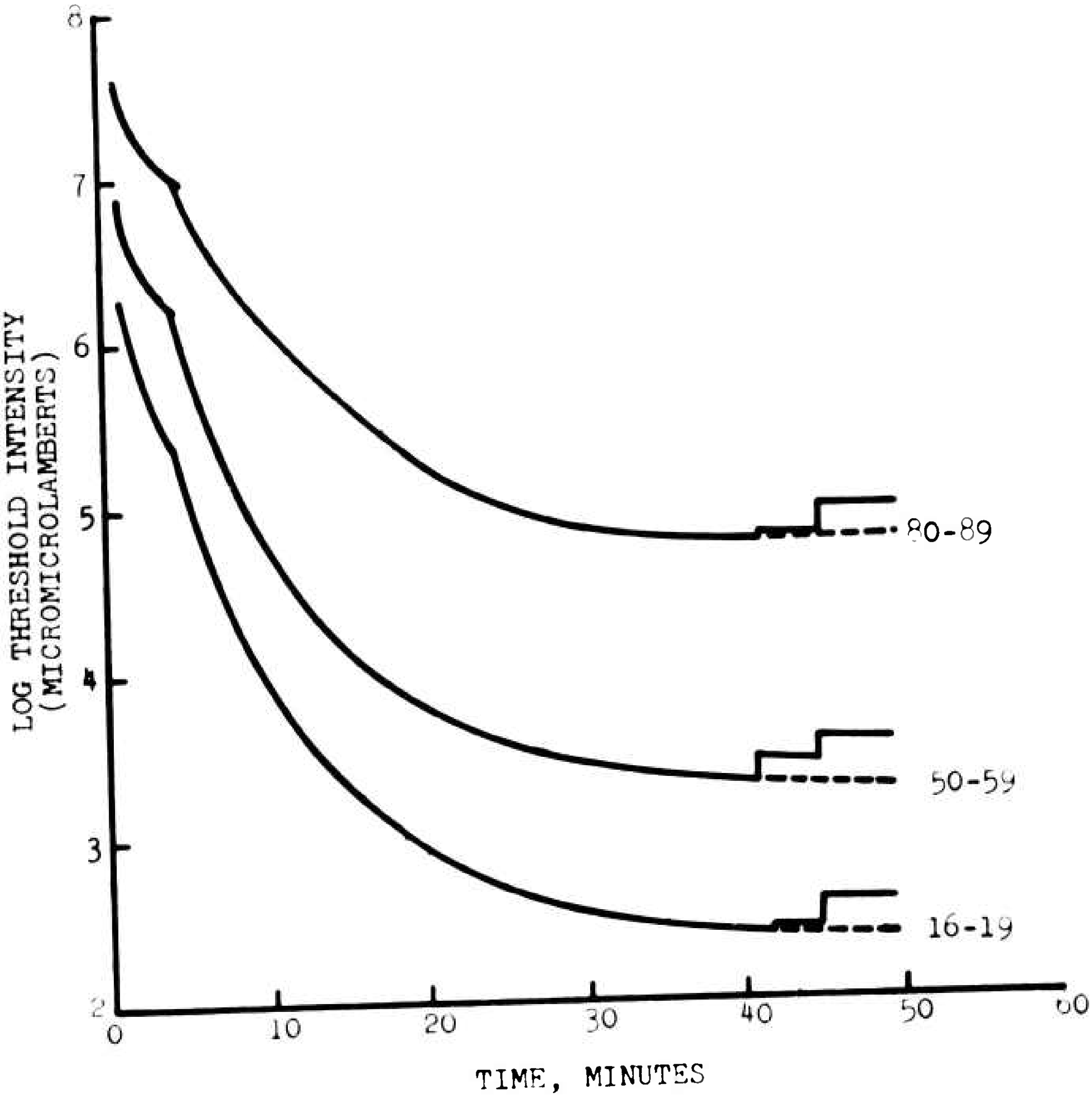

Fig. B-8. Dark adaptation as a function of age. (After McFarland, Domey, Warren, & Ward, 1960.)

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