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The Eye and Night Vision

(This article has been adapted from the excellent USAF Special Report, AL-SR-1992-0002, "Night Vision Manual for the Flight Surgeon", written by Robert E. Miller II, Col, USAF, (RET) and Thomas J. Tredici, Col, USAF, (RET))

THE EYE

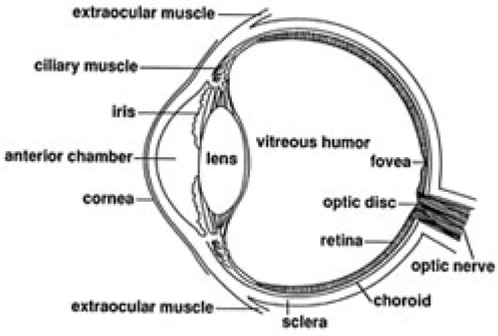

Figure 2-1
Schematic diagram of the eye

The basic structure of the eye is shown in Figure 1. The anterior portion of the eye is essentially a lens system, made up of the cornea and crystalline lens, whose primary purpose is to focus light onto the retina. The retina contains receptor cells, rods and cones, which, when stimulated by light, send signals to the brain. These signals are subsequently interpreted as vision.

Most of the receptors are rods, which are found predominately in the periphery of the retina, whereas the cones are located mostly in the center and near periphery of the retina. Although there are approximately 17 rods for every cone, the cones, concentrated centrally, allow resolution of fine detail and color discrimination. The rods cannot distinguish colors and have poor resolution, but they have a much higher sensitivity to light than the cones.

DAY VERSUS NIGHT VISION

According to a widely held theory of vision, the rods are responsible for vision under very dim levels of illumination (scotopic vision) and the cones function at higher illumination levels (photopic vision). Photopic vision provides the capability for seeing color and resolving fine detail (20/20 of better), but it functions only in good illumination. Scotopic vision is of poorer quality; it is limited by reduced resolution (20/200 or less) and provides the ability to discriminate only between shades of black and white. This limitation can be easily confirmed by noting that, at dusk, the different colors of a flower garden become virtually indistinguishable. However, the scotopic system provides enhanced sensitivity and low detection thresholds under markedly reduced illumination.

This dual-receptor system allows the human eye to maintain sensitivity over an impressively large range of ambient light levels. Between the limits of maximal photopic vision and minimal scotopic vision, the eye can function rather effectively to changes in brightness of as much as 1,000,000,000 times. The sensitivity of the eye automatically adjusts to changes in illumination. The dimmest light in which the rods can function is equivalent to ambient conditions of an overcast night with no moonlight. The dimmest light in which the cones can function is roughly equivalent to a night with 50% moonlight. Thus a white which can just barely be seen by the rods must be increased in brightness 1,000 times before it becomes visible to the cones. The light intensity of the sun is approximately 30,000 times that of the moon, yet the eye can function well in bright sunlight as well as in dim moonlight. Although the human eye can function over a vast range of brightness, the retina is sensitive to damage by light, e.g., from lasers or unprotected sun gazing. This potential for light injury exists because the optics of the eye can concentrate light energy on the retina by a factor of 100,000 times.

MESOPIC VISION

There is a common misconception that the rods are used only at night and the cones only during the day. Actually, both rods and cones function over a wide range of light intensity levels and, at intermediate levels of illumination, they function simultaneously. The transition zone between photopic and scotopic vision where the level of illumination is equivalent to twilight or dusk, is called mesopic vision. Neither the rods nor the cones operate at peak efficiency in this range, but both actively contribute to visual perception. Mesopic vision may be of primary importance to the aviator at night because some light is often present during night operations. Below the intensity of moonlight, the cones cease to function and the rods alone are responsible for what is pure scotopic vision.

DARK ADAPTATION

Dark adaptation is an independent process during which each eye adjusts from a high-luminance setting to a low-luminance setting. The exact mechanisms are unclear, but they are known to include biochemical, physical, and neural.

Both rods and cones contain light-sensitive chemicals called photopigments. The photopigment in the rods is called rhodopsin. There are three different types of cone photopigments that are composed of opsins only slightly different from rhodopsin. Upon exposure to light, photopigments undergo a chemical reaction that converts light energy to electrical activity, initiating visual impulses in the retina that are conducted by nerve fibers from the eye to the brain. The initial chemical reaction is called light adaptation and, in this process, the photopigments are decomposed. Intense light will decompose the photoreceptor pigments rapidly and completely, thus reducing retinal sensitivity to dim light. Regeneration of the photopigments occurs during dark adaptation.

The fully dark-adapted eye, in which photopigment regeneration is complete, restores retinal sensitivity to its maximal level. Rods and cones differ markedly, however, in their rate of dark adaptation. Cones attain maximum sensitivity in 5-7 minutes, while rods require 30-45 minutes or longer of absolute darkness to attain maximum sensitivity after exposure to bright light.

The cones have a faster rate of photochemical regeneration because they function in greater light than the rods. The cones, however, do not achieve the same level of sensitivity as the rods. The rods slowly adapt to dim illumination, but eventually achieve a much greater sensitivity than the cones. Depending on the preadaptation to light, dark adaptation is about 80% complete within 30 minutes, but it may take hours, or even days, to acquire total dark adaptation.

In addition to adaptation caused by changes in photopigment concentrations, the eye has other mechanisms for adapting to changing light conditions. Retinal adaptation can be affected by physical changes in the size of the pupil. The diameter of the pupil can contract to 1.5mm and expand to 8mm, which equates to a 30-fold range in the quantity of light entering the eye.

Another light-adaptive mechanism is neural adaptation, which is generated by retinal neurons at successive stages of the visual chain in the retina. A change in "neural gain" occurs in seconds and can improve night vision by a factor of 10 or more. Neural adaptation is rather like having low-speed and high-speed film simultaneously available in your camera. Furthermore, a large share of the inherently greater sensitivity of rod dark adaptation is a result of retinal summation. As many as 100 rods, or more, converge onto a single nerve fiber in the retina, which greatly increases sensitivity. Thus, if the rods are slightly stimulated, the summation of several low-level stimuli might be enough to initiate a light signal to the brain. Unlike the photoreceptor chemical changes, these mechanisms occur instantaneously.

CENTRAL BLIND SPOT AT NIGHT

That portion of the retina responsible for the keenest visual acuity (VA) is the fovea, which corresponds to the center of the visual field. The foveola, or center of the fovea, possesses a high degree of cones, but is completely devoid of rods. Thus, if the ambient light is below cone threshold, when any small object is fixated centrally, it cannot be seen because, at light levels below dim starlight, a blind spot exists in the central 1 degree of the visual field. This central blind spot corresponds to the foveola, which is rod-free; it cannot function in diminished illumination.

Rods are present outside the central 1-degree foveolar area. The rods increase gradually with eccentricity from the foveola, and finally reach a maximum concentration at a point some 17 degrees from the fovea. Since the rods have a lower threshold than the cones, they are much more sensitive to light. A person attempting to see in scotopic illumination, light dimmer than moonlight, has to depend entirely on rods. To best detect small targets with the rods under such circumstances, the individual must look approximately 15-20 degrees to one side, above, or below an object to place the object of regard on the part of the retina that possesses the highest density of rods. Individuals can be taught to fixate to one side of an object to avoid the central blind spot and to scan, utilizing the most sensitive part of the retina to improve target detection at night. Therefore, proper education and training are helpful in maximizing visual function at night.

SPECTRAL SENSITIVITY

That part of the electromagnetic energy spectrum which stimulates the photoreceptors in the retina is known as visible light. Visible light includes violet, indigo, blue, green, yellow, orange, and red, i.e., a range of wavelengths extending from about 380nm to 760nm. Adjacent portions of the spectrum, although not visible, can affect the eye. Ultraviolet wavelengths extend from 180nm to 380nm. Exposure of the eyes to ultraviolet radiation can produce eye tissue damage. Acute overexposure can cause photokeratitis, commonly called snow blindness, while chronic exposure has been implicated as a possible cause of cataracts. Infrared wavelengths occur from 760nm up to the microwave portion of the spectrum. Infrared, or thermal radiation, can also damage ocular tissue. However, infrared does not contain as much energy as shorter wavelength ultraviolet. Most night vision devices are sensitive to portions of the infrared spectrum.

PURKINJE SHIFT

Rods and cones are not equally sensitive to visible wavelengths of light. Unlike the cones, rods are more sensitive to blue light and are not sensitive to wavelengths greater than about 640nm, the red portion of the visible spectrum.

The Purkinje shift is the relatively greater brightness of blue or green light, compared with yellow or red light, upon shifting from photopic to scotopic adaptation. For example, in a darkened room, if one looks at two dim lights of equal illumination (one red and one green) that are positioned closely together, the red light will look brighter than the green light when the eyes are fixating centrally. If one looks to the side of the dim lights about 15-20 degrees, the green light will appear brighter than the red. Central fixation involves the cones and photopic vision while fixating eccentrically involves rods and scotopic vision. The cones are more sensitive to yellow and red, but the rods are more sensitive to light of the blue and green wavelengths. The most sensitive wavelength for cones is 555nm (yellow-green). That is why the "optic yellow" tennis and golf balls are, in fact, easier to see under photopic conditions. The most sensitive wavelength for rods is 505nm (blue-green). Thus, blue-green lights will generally look brighter at night than red lights. The sensitivity of the eye changes from the red end of the visible spectrum toward the blue end when shifting from the photopic to scotopic vision.

PHOTOCHROMATIC INTERVAL

An appropriate demonstration of the difference between photopic and scotopic sensitivity is to slowly decrease the intensity of a colored light until the cone threshold is reached. This is the point at which the color will disappear, but not the sensation of light. When this procedure is performed with any color except red, the color will disappear at the cone threshold, but the light will still be perceived by the rods as dim gray. If the intensity is further decreased until the rod threshold is reached, the light will disappear entirely. With red light, the color and sensation of light disappear at the same time.

The difference between the level of illumination at which the color of a light disappears (cone threshold) and that at which the light itself disappears (the rod threshold) is known as the photochromatic interval. There is a photochromatic interval for every color of the spectrum, except for the longer red wavelengths.

NIGHT BLINDNESS

True night blindness is unusual. Night blindness can be caused by long-term vitamin A deficiency such as may occur from chronic starvation, alcoholism, deficient fat absorption, and diseases of the liver. Retinal conditions that may cause night blindness are glaucoma, drug toxicity and numerous hereditary disorders. Although not true night blindness, night myopia may also reduce night vision. Considerable individual variability exists in retinal sensitivity to light among normals. Also, as people age, night vision decreases.

PHYSIOLOGIC BLIND SPOT

Each eye also has a physiologic blind spot. Unlike the central blind spot that is only present in low light, the physiologic blind spot is always present. It is caused by the position of the optic nerve in the rear of the eye. The optic nerve is the confluence of retinal nerve fibers leaving the eye. There are no retinal receptors overlying the optic nerve. Fortunately, the physiologic blind spots occur in a different position in each eye. Thus, when both eyes are open, the physiologic blind spots are not apparent.

OPERATIONAL ASPECTS OF NIGHT VISION

INTRODUCTION

The effects of decreased illumination on operational visual function can be dramatic. Visual acuity may be reduced to 20/200 or less, color vision is lost, blue-green lights will appear brighter while red lights will appear dimmer, problems may occur with night myopia, depth perception is degraded, glare is a factor, and a central blind spot is present. The potential effects of these factors on the operational aspects of night vision will now be considered.

CONTRAST DISCRIMINATION

Visual acuity is reduced at night under low illumination and 20/20 vision cannot be sustained below a level of deep twilight. Objects can be seen at night only if they are either lighter or darker than their background and can be discriminated by subtle differences in contrast. Because VA at night is a function of small differences in the brightness (luminance contrast) between objects and their background, any transparent medium through which the flyer must look should be kept spotlessly clean. Contrast discrimination may be reduced by light reflected from windshields, visors, spectacles, fog, or haze.

Knowledge of the importance of contrast at night was used by pilots during World War II to detect enemy planes, as well as to hide their own positions. Pilots would fly below the enemy when passing over dark areas, such as land, or when flying over an area illuminated by multiple points of light, such as a large city at night. Conversely, they would fly above the enemy when passing over white clouds, desert, moonlit water, or snow. Following another aircraft from above or below, rather than from directly behind, will maintain the largest retinal image and lessen the likelihood of losing sight of the other aircraft in the darkness.

NIGHT MYOPIA

Flyers who do not normally wear spectacles, or those who wear visual correction, may have a small myopic shift under extremely reduced illumination. This near-sighted or myopic shift is called the dark focus of the eye. The dark focus of the eye may become a problem whenever there is a lack of adequate distance objects upon which to focus. For most people, night myopia has a relatively minor effect because no visually resolvable distant target is present when it occurs. When a target does become visible, the eye rapidly readjusts. Since night myopia does not occur in the cockpit when the crew is operating under photopic conditions, it is probably more of a theoretical concern.

ENHANCING AND MAINTAINING DARK ADAPTATION

Red Goggles or Spectacles

For maximum utilization of scotopic vision, 20 to 30 minutes in total darkness are required to attain satisfactory retinal dark adaptation. An alternative is to have the aircrew member wear red goggles for 20 to 30 minutes before flying. When worn in normal illumination, red goggles will not interfere significantly with the ability to read most maps, charts, manuals, etc., as long as the printing is not in red ink. Red goggles block all light except red, which enhances rod dark adaptation because red light does not stimulate the scotopic system.

There are some drawbacks to wearing red goggles or using red cockpit lighting. When reading maps, markings in red on a white background may be invisible. Red light also creates or worsens near-point blur in older far-sighted, presbyopic (decreased near focusing ability due to age), and pre-presbyopic aircrew. Under red light or using red goggles in normal light, red light is focused behind the retina due to the optics of the eye and more "near focusing" than average must be used to provide a clear image when reading at near.

Flash Blindness

While dark adaptation of the rods develops rather slowly over a period of 20 to 30 minutes, it can be lost in a few seconds of exposure to bright light. Accordingly, during night operations aircrew members should be taught to avoid bright lights, or, at least, protect one eye. Dark adaptation is an independent process in each eye. Even though bright light may shine into one eye, the other eye will retain its dark adaptation if it is protected from the light. This is a useful bit of information, because a flyer can prevent flash blindness and preserve dark adaptation in one eye by simply closing or covering it. The instrument panel should be kept illuminated at the lowest level consistent with safe operation, and the flyer should avoid looking at exhaust flames, strobes, searchlights, etc. to avoid temporary flash blindness. If light must be used, it should be as dim as possible and should only be used for the shortest possible period.

Daytime Exposure

Daytime exposure to ordinary sunlight can produce temporary but cumulative aftereffects on dark adaptation and night vision. Both civilian and military studies have documented significantly diminished rod performance after prolonged sunlight exposure at, for example, the beach or ski slope. Two or three hours of bright sunlight exposure has been shown to delay the onset of rod dark adaptation by 10 minutes or more, and to decrease the final threshold, so that full night vision sensitivity could not be reached for hours. After 10 consecutive days of sunlight exposure, the losses in night vision were reported to cause a 50 % loss in visual acuity, visibility range, and contrast discrimination. Repeated daily exposures to sunlight prolong the time to reach normal scotopic sensitivity, so that eventually normal rod sensitivity may not be reached.

There are several means for providing eye protection during the day and conserving night vision. First, aircrew members should remain inside during the day of a night flight, if at all possible.

Sleeping during the day in a darkened room is highly recommended. While outside, aviators should wear their sunglasses and a hat with a brim, which will block a great deal of ambient solar radiation. Dark sunglasses that transmit only 15% of the visible light will prevent degradation of night vision. In general, one day of protection from sunlight exposure was usualy sufficient to recover normal vision sensitivity. However, in certain individuals, it may take days to weeks to recover full night vision capability.

For sunglasses to be effective, all visible light must be attenuated, not just portions of the visible spectrum. Thus, colored or yellow visors or spectacles are not protective. To protect night vision, provide the best comfort, allow for scanning close to the sun, and provide normal color vision, dark sunglasses with a neutral gray tint are recommended. Tinted sunglasses that are too dark may reduce visual acuity unless the ambient brightness remains excessively high. Lighter sunglasses may not be dark enough to protect retinal sensitivity for night vision. Therefore, it has long been recognized that military flyers should be required to use sunglasses on sunny days. These sunglasses should have a visible luminance transmission of 15%. Anyone who is unusually sensitive should remain indoors during the afternoon before a night mission. Pilots should ensure that they wear sunglasses or sunvisors when flying on sunny days.

COCKPIT ILLUMINATION

Red light was used for illumination of the cockpit in post-World War II aircraft because it, like red goggles, did not degrade dark adaptation. The intent was to maintain the greatest rod sensitivity possible, while still providing some illumination for central foveal vision. However, red cockpit lights interfered with reading maps and log books, especially for pre-presbyopic and presbyopic aviators. With the increased use of electronic and electro-optical devices for navigation the importance of the pilot's visual efficiency in the cockpit has increased and new concerns have arisen.

Low intensity, white cockpit lights are often used now because they afford a more natural visual environment within the aircraft, without degrading the color of objects.

VISUAL ILLUSIONS AT NIGHT

Reduced visual references, due to low ambient light levels, can lead to several types of visual illusions that may cause spatial disorientation. There are two forms of visual processing, central (foveal) and peripheral (ambient). Whereas central vision is predominately concerned with object recognition and discrimination, peripheral vision provides motion detection and spatial orientation information. At night, under reduced illumination levels, the normal peripheral vision cues may be degraded or absent, and spatial disorientation may be more difficult to overcome. Spatial disorientation may arise from labyrinthine, proprioceptive, or visual mechanisms.

Autokinetic Effect

Autokinesis, or the autokinetic effect, is the phenomenon of perceived movement exhibited by a static dim light when it is stared at in the dark. This effect can be demonstrated by staring at a lighted cigarette in a dark room. The dim light will appear to move about, even though it is stationary. Although the exact cause of this illusion is not known, it is related to tiny fixation movements of the eye and the loss of the surrounding references which normally stabilize visual perception. This illusion will also occur when there are two dim lights in darkness, but it normally disappears when three or more lights are present. Pilots on night flights have mistaken stars or ground lights for other aircraft and have become disoriented, with fatal consequences. Therefore, pilots should be aware of this visual illusion. The autokinetic effect can be reduced by maintaining good visual scanning techniques rather than staring at the light source, or by increasing the intensity of the lights, if that is possible.

Black Hole Illusion

The black hole illusion may occur on a dark night over water or unlighted terrain where the horizon is not easily discernible. The worst case occurs when there are no visual references except for runway lights. Without peripheral cues for orientation, the pilot tends to perceive that his/her aircraft is stable, but that the runway itself is out of position, usually sloping down. The black hole illusion makes the landing approach dangerous, and often results in a landing far short of the runway. A particularly hazardous type of black hole approach occurs when the earth appears to be totally dark except for the runway and the lights of a city on rising terrain beyond the runway. By maintaining a constant vertical visual angle on the distant city lights, the pilot's approach may fall below the intended glideslope as the aircraft gets closer to the runway.

Distance Illusion Phenomenon

The distance illusion phenomenon is a dangerous illusion (DIP) that can occur when one aircraft is trailing another in a black hole environment with few peripheral vision cues. A likely scenario for the DIP occurs the trailing aircraft pilot, for position reference, places the image of the lead aircraft on a certain spot in his canopy. The pilot orients the lead aircraft in exactly the same spot on the canopy, but, over time, inadvertently falls back to a greater separation distance. If the trailing aircraft started out 2 nautical miles behind and 300 feet below the lead aircraft and then fell back to 4 nautical miles, that would mean that the trailing aircraft was now 600 feet below the lead. If the lead aircraft gradually descends to 600 feet or less, the trailing aircraft may impact the ground. The potential mishap exists only if the pilot maintains the lead aircraft in exactly the same spot on the canopy, but fails to monitor the actual altitude or fails to realize that the separation distance has increased.

False Perceptions

Pilots are especially susceptible to misperception of the horizon while flying at night. To a pilot, isolated ground lights can look like stars and create the false impression of a nose-high pitch or wing-low attitude. If no stars are visible because of overcast conditions, unlighted areas of terrain may blend with the dark overcast to create the illusion that the unlighted terrain is part of the sky. An extremely hazardous takeoff occurs over an ocean or other body of water that cannot be distinguished visually from the night sky; pilots who have falsely perceived that the shoreline receding beneath them was the horizon have met with disastrous consequences.

At night, if runway lights viewed from an approaching aircraft are displaced laterally, the pilot may have the impression that the runway is closer than it really is, because it appears wider. This false perception may result in an early flare and a tendency to land short. Also, the intensity of runway lights may appear to vary, depending on their color and the adaptation states of the eyes. These differences in the brightness of runway lights may lead to false perceptions regarding altitude.

Pilots are aware of certain vestibular illusions that may be more difficult to overcome during nighttime operations. Somatogravic illusions are false perceptions of the body's orientation to gravity. Somatogyral illusions are experienced by pilots during maneuvers of sustained angular motion such as coordinated turns, spins, or rolls. These illusions result from the inability of the semicircular canals of the inner ear to register sustained angular velocity. The lack of visual cues at night may make these illusions more troublesome.

MEDICATIONS

The effects of smoking tobacco products on night vision are controversial. Early studies showed a significant decrease in scotopic dark adaptation with smoking, which was attributed to the hypoxic effects of carbon monoxide (CO). Later studies found that smoking seemingly improved night visual performance on some psychophysical tests. This improvement was presumed to be a result of the stimulant effect of nicotine. More recent studies have reported that smokers have reduce mesopic vision when compared with nonsmokers.

Although the literature is somewhat confusing, smoking is discouraged for several reasons. First, there is some evidence that it may degrade mesopic and night vision. Second, although many night flights are low level, the hypoxic effect of CO is additive with altitudinal hypoxia. Third, secondary smoke is a significant irritant for aircrew who wear contact lenses or for those with dry eyes. Fourth, smoke forms filmy deposits on windscreens, visors, and spectacles that can degrade contrast at night. Fifth, the effects of smoking withdrawal during long missions may be dangerous. Finally, the chronic long-term effects of smoking are hazardous to overall health.

HYPOXIA

The effect of altitudinal hypoxia on night vision is primarily one of an elevation of the rod and cone threshold. Although decreased cone function is clearly demonstrated by the loss of color vision at hypoxic altitudes, the decrement in central VA is usually insignificant. However, scotopic night vision at altitude can be significantly reduced. Scotopic vision has been reported to decrease by 5% at 3,500 feet, 20% at 10,000 feet, and 35% at 13,000 feet, if supplemental oxygen is not provided. Thus, the use of oxygen, even at low pressure altitudes, can be very important at night.

RECOMMENDATIONS

The following are some ways for aviators to protect, improve, or maintain their operational night vision.

1. Complete a training course that emphasizes the inherent limitations of night vision
2. Keep spectacles, visors, and windscreens clean
3. Wear proper spectacle correction.
4. When practical, dark-adapt or use red goggles before night flying
5. Avoid bright lights, or at least protect one eye.
6. Do not fixate centrally, but scan and look 15-20 degrees to the side of the visual target.
7. Regularly wear sunglasses on sunny days, especially on days of night missions.
8. Eat an adequate diet that includes vitamin A.
9. Do not smoke.
10. Consider use of 100% oxygen at night, even at low altitudes.