Chapter 5

LASER GLARE EFFECTS ON VISUAL PERFORMANCE

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INTRODUCTION

There have been many studies of the threshold energy required for laser-induced ocular damage. However, exposure to a visible laser that does not produce irreversible ocular damage can still result in substantial visual impairment through temporary mechanisms, such as glare and flash blindness. Visual deficits like these can disrupt visual performance and thus compromise the safety and success of military operations. The severity of laser glare and subsequent visual recovery depends on a number of factors, including parameters of laser exposure, presence of intervening optical materials, and requirements of the visual task.

Units of Measurement

Optical radiation can be described by two systems of terms and measurements: (1) radiometric quantities and (2) photometric quantities. The *radiometric system* is a physical system that can be applied throughout the electromagnetic spectrum. The *photometric system* is used only to describe visible radiation (ie, electromagnetic radiation in the range of wavelengths from approximately 400 to 700 nm).

Radiometric Quantities

In the context of this chapter, radiometric quantities are used only in relation to the characteristics of laser radiation. The radiometric quantities (and units) referred to here are

- radiant energy (J),
- radiant power (W),
- radiant exposure (energy per unit area of absorbing source, J • m^{-2}), and
- irradiance (power per unit area of absorbing source, W • m^{-2}).

Safe exposure limits are generally defined in terms of radiant exposure and irradiance.

Photometric Quantities

Although laser sources are usually described in terms of radiometric quantities, these give no indication of the effectiveness of the source as a stimulus for vision. The photometric system was developed to describe optical radiation in terms of its ability to elicit a response from the visual system. The basic unit of photometry is the lumen (lm), which is the photometric equivalent of the watt (W). Under photopic conditions, 1 W of radiant flux at 555 nm is, by definition, equivalent to 683 lm of luminous flux.[1] This wavelength is the peak of the sensitivity of the eye under photopic viewing conditions. The relative sensitivity of the eye to other wavelengths is defined by the International Commission on Illumination[2] (CIE) as the relative photopic spectral luminosity function, V_λ, for a standard observer (Figure 5-1). This function is given a value of unity at its maximum of 555 nm. For a laser with a radiant power (flux) of P in W at 555 nm, the luminous power (flux [in lm]) will be 683 × P lm. To generalize to any laser wavelength, λ, the luminous flux, ϕ_v, is calculated as:

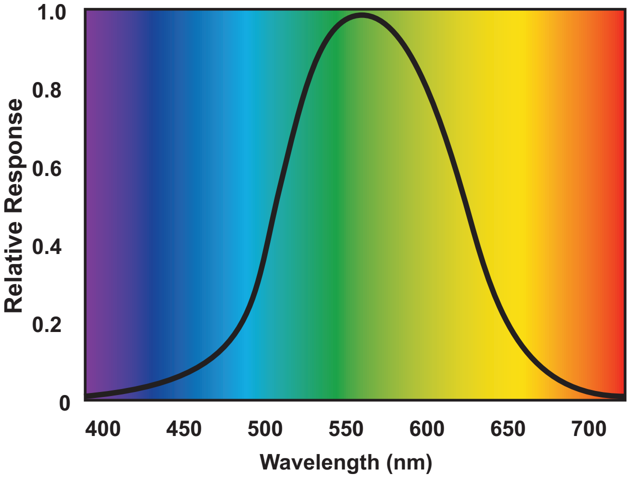

Figure 5-1. The CIE photopic spectral luminosity curve for the standard observer. The curve has a peak sensitivity at 555 nm and declines toward zero at 400 and 750 nm.
CIE: International Commission on Illumination

$$\phi_v = 683 \times P \times V_\lambda$$

where

P = radiant power at this wavelength, and
V_λ = value of the relative spectral luminosity function at this wavelength.

NORMAL VISUAL ADAPTATION

The human visual system is capable of retaining its ability to detect a change in visual stimulation (sensitivity to light) over a wide range of illumination levels (Figure 5-2). Adaptation refers to the processes by which the system maintains sensitivity to changes in illumination. The mechanisms by which the human

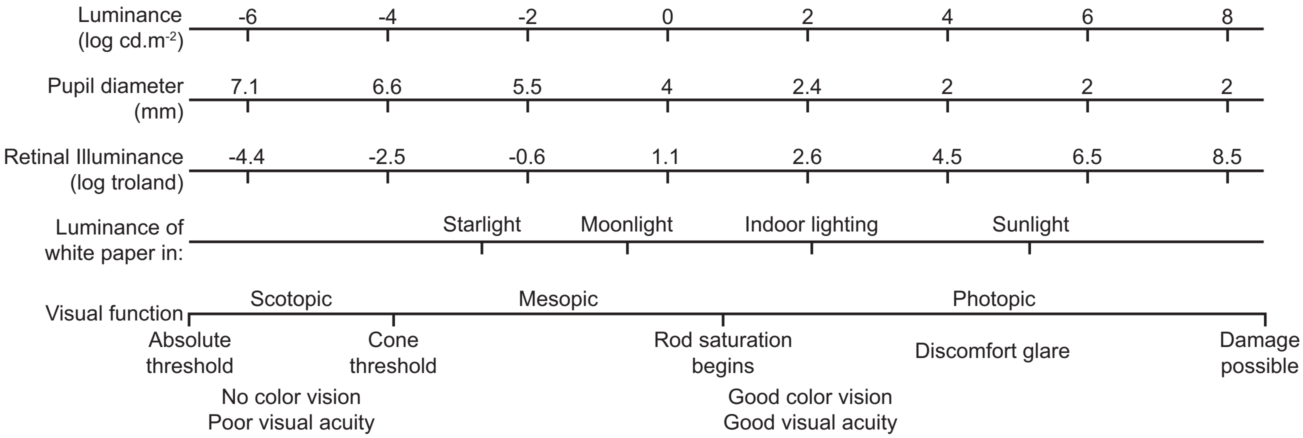

Figure 5-2. Visual function in relation to the normal range of light intensities confronting the human eye.

eye and visual system adapt to light can be grouped into three gross divisions: (1) mechanical, (2) photochemical, and (3) neurophysiological.

Mechanical Mechanisms

Mechanical adaptation mechanisms include the constriction of the pupil of the eye and, in extreme cases of intense light exposure, the blink reflex, and the natural aversion response to bright lights.

Pupillary Constriction

The iris controls the aperture of the refracting system (*the pupil*) of the eye. The iris acts as a diaphragm. It constricts or dilates through the opposing action of two sets of muscles: (1) the sphincter pupillae and (2) the dilator pupillae. Pupil size is thus governed by the refractive state of the eye and in response to the average brightness of the scene being viewed.[3,4] In an adult human, maximum pupil diameter in the dark is approximately 8 mm, although larger pupil diameters have been documented.[5] Current laser safety standards accept a value of 7 mm as a worst-case maximum pupil diameter. The pupil has a complex response to bright light exposure,[6] but on prolonged exposure will generally constrict to a minimum pupil diameter of approximately 2 mm.

The amount of light that enters the eye is directly proportional to the area of the pupil. Pupil diameter range (2–8 mm) allows for a 16-fold change in pupillary area. For a large change in illumination, pupillary constriction and dilation response times are fairly slow, reported at 0.2 and 0.5 s, respectively.[6] These response times are wholly inadequate to protect the human eye from intense light sources.

Although the pupil plays a useful role in the adaptation of the eye to changes in luminance level, it clearly lacks the dynamic range to support changes much beyond an order of magnitude. The pupil assumes a greater role in image formation in the eye. Optical aberrations are much greater in the periphery of the cornea and the lens.[7,8] Pupillary constriction excludes light that passes through the peripheral portions of these structures. Constriction also serves to increase depth of focus and occurs synergistically with accommodation for near objects. Under normal lighting conditions, the operating diameter of the pupil is between 2 and 4 mm.

Blink Reflex

Reflexive blinking can be evoked by almost any peripheral stimulus. The two most functionally significant reflexes are (1) the sensory blink reflex (which is caused by corneal stimulation) and (2) the optical blink reflex (which is caused by bright lights). Only the optical blink reflex is relevant to protecting the eye from overexposure to visible light. The latency of the optical blink reflex depends on the magnitude of the stimulus, but for the brightest lights would typically occur at about 250 ms.[9] Indeed, safety standards for some visible lasers (class 2) apply a 250 ms exposure time on the premise that aversion response (which includes the optical blink reflex) will limit exposure to this period of time.[10]

The blink reflex plays a very important role in protecting the eye. However, even when the eyelids are shut, the human eye can perceive the brightness of an external scene. Although detailed vision is not possible, changes in illumination level are still apparent. The human eyelid has a transmission ranging from approximately 0.3% in the blue region of the spectrum to 5.6% in the red region.[11] With regard to the normal processes of visual adaptation, however, the blink reflex is of little value when the eyelids are closed. In this state, the light level to which the visual system must adapt is greatly attenuated, and useful vision is lost until the lid reopens.

Photochemical Mechanisms

The presence of a steady level of illumination on a retinal photoreceptor bleaches a portion of the retinal photopigment and reduces the number of pigment molecules that remain in an unbleached, active state. This depletion of photopigment contributes to a loss in sensitivity with increasing field intensity. Under steady-state conditions, the increase in threshold should be inversely proportional to photopigment content. For example, halving the number of available molecules would be expected to double the threshold intensity. However, Aguilar[12] and Stiles[13] demonstrated that the visual system loses at least five to six log units of sensitivity before the photopigment is depleted by even a few percent. Within the range of normally encountered intensities, pigment depletion plays a small role in adaptation. At high luminance, however, pigment depletion accounts for all of the loss in sensitivity.[14]

If a light source is sufficiently bright, the subjective sensation may last much longer than the stimulus itself. It is this persistence that causes a moving light to be seen as a line or a flickering light to appear fused when the rate of flicker is sufficiently high. Remnants of past stimulation are known as *afterimages* and may continue for a relatively long period of time. Studies of afterimages have shown that they are the result of persistent photopigment changes that follow bleaching.[15,16] The luminance of a surface judged to be exactly as bright as an afterimage has been shown to be proportional to the fraction of the photopigment that remains bleached.[17] Additional discussion of afterimages will appear later in this chapter.

Neurophysiological Processes

Although pupillary constriction and the depletion of photopigment both alter the adaptive state of the visual system, neurophysiological adaptation mechanisms exert more functionally significant effects. These processes are known as *spatial and temporal induction and summation*.

Spatial induction, or simultaneous contrast, refers to the observation that the effect of light falling on a given portion of the retina is generally not confined to the stimulated retinal elements. For example, a gray square viewed against a black background will appear as almost white, whereas the same gray square seen against a white background will appear to be much darker. The white surround has the effect of depressing the sensitivity of the entire retina, which makes the gray appear darker. The effect of *temporal induction,* or light adaptation, is similar. If the entire retina is stimulated with white light, its sensitivity to a subsequent second stimulus will be reduced.

Ricco's law of areal or *spatial summation* states that when a stimulus is small and brief, the visual system shows complete summation over space and time.[18] For small test stimuli, there is an inverse relationship between the area of the stimulus and the intensity required for its detection. Bloch[19] showed that a similar relationship exists between stimulus duration and threshold. Bloch's law of *temporal summation* states that the threshold remains the same as long as the product of stimulus intensity and duration (ie, the number of quanta) is held constant. This is true for stimulus durations shorter than a critical period of about 100 ms.[14] For slightly longer exposures, there occurs a phenomenon known as *brightness enhancement*, or the *Broca-Sulzer effect*, whereby a brief flash of light may appear to be brighter than a steady light of equivalent luminance.

TEMPORARY CHANGES IN VISUAL SENSITIVITY

Transient decrements in visual performance may be caused by artificial light sources at exposure levels that are lower than the levels necessary to cause permanent retinal damage. Unfortunately, the literature is inconsistent with respect to nomenclature used to describe these effects. Terms such as g*lare, dazzle, flash blindness*, and *afterimages* are widely used, but are ill-defined and often used interchangeably.

Glare

Glare can be described as the hindrance to vision that is caused by too much light. Glare has been formally defined as any degree of light falling on the retina in excess of that which enables an individual to see clearly. In other words, glare is caused by any excess light that hinders rather than helps vision.[8] If glare is sufficiently intense, it can temporarily reduce the sensitivity of the visual system even after the source of glare is removed from the field of view. For example, a photographic flash often causes temporary flash blindness and afterimages. These phenomena are a function of retinal and visual pathway processes that will be discussed in more detail later in this chapter.

Glare phenomena have been differentiated into a variety of subcategories. As early as 1922, the Illumination Engineering Society of New York charged a subcommittee with investigating the subject of glare to "furnish a sound foundation for definite research regarding the matter."[20(p743)] Based on the nature of the light source and particular types of resulting visual interference, three types of glare were identified:

1. veiling glare,
2. dazzle glare, and
3. scotomatic glare.

More recently, Vos[21] defined three expressions of glare as:

1. *Disability glare* refers to a masking effect that occurs when one or more bright lights are in close proximity to the object under view. Light scatter from the optic media results in the superimposition of a veil of light on the image of viewed object. This, in turn, reduces the object's contrast and thus its visibility. Although absolute foveal illumination is increased, the concomitant reduction in image contrast makes detailed discrimination more difficult.
2. *Discomfort glare* refers to the distracting effect of a peripheral light source in the field of view. This phenomenon involves the same configuration as disability glare, but the effect is different. Discomfort glare does not necessarily impair the visibility of objects. Rather, the emphasis here is on the distracting effect. Discomfort glare is typically associated with bright light sources, such as road luminaries or ceiling spots, that attract attention and catch one's gaze. This causes visual discomfort, but is not due to light overexposure.
3. *Dazzling glare* refers to the effects of an excessively bright field of view (eg, sunlight, snow, sky) that causes one to squint, avert gaze, don sunglasses, or take some other action to avoid the light. Overexposure to light may even be painful. If present, the pain probably originates in the sphincter muscle of the iris, which may spasm in an effort to overconstrict. The retina of the eye itself has no pain receptors.

Equivalent Background Luminance Concept

This concept (or equivalent veiling luminance) was developed in an effort to extrapolate the effect of a disability glare source to a wide variety of visual tasks. It was first introduced by Cobb[22] and later elaborated by Holladay,[23,24] and the initial application was in relation to glare from car headlights. These studies showed that in the presence of a glare source, vision is impaired just as if a veil of light was cast over the objects in the field of view. The visual effect of the source could be described by superimposing an external luminous field onto the scene. The effect could thus be expressed in terms of steady luminous field intensity or "equivalent background," which has an equivalent effect on target visibility. Equivalent background produces a contrast threshold elevation identical to that produced by the glare source.

Similar effects have been shown with afterimages. The contrast of a visual target viewed through an afterimage is reduced just as if a physical luminous background had been superimposed on the affected portion of the visual scene. Crawford[25] established a relationship between the equivalent background luminance and elapsed time for detection of a variety of simple targets following flashes of various energies. By measuring the background luminance for threshold detection of any target configuration at a given illuminance level, Crawford was able to predict the recovery time for that target following a known flash energy. The value of the equivalent background luminance technique lies in its predictive capability through its generalizability to other target conditions.

A great deal of evidence supports the equivalent background hypothesis in the human rod system,[17,26–28] and further studies have extended the hypothesis to cone functions.[29,30]

The application of the equivalent veiling luminance technique to afterimage research has been largely limited to the studies performed by Miller.[31–33] In the first of these studies, Miller[31] alluded to the fact that equivalent background may be useful to predict recovery times. In her later studies, she realized the full benefits of the technique and was able to predict recovery times from afterimage brightness measurements.

Factors Affecting Laser Glare Effects

Retinal Light Distribution

In a perfect optical system, the light from a laser would be seen by the eye as if it were coming from a point source. This would mean that only a small portion of the visual field would be affected. In reality, however, the eye may not be able to form a perfect image of the laser source. This is due to the scattering properties of the atmosphere, intervening optical materials, and the ocular media of the eye itself. If the scatter is of sufficient magnitude, the image will appear as a sharp, intense central peak surrounded by widely scattered radiation.

Intraocular Scatter. Although in principle the light from a point source should be imaged on the retina as a point, in reality focused rays do not all converge on the retina as a single spot. Optical imperfections (eg, spherical and chromatic aberrations, diffraction effects, and refractive errors) cause blurring.[34-37] Retinal image quality is further degraded by stray light from intraocular scatter, which spreads approximately 8% of the incident light.[38] The cornea, lens, and fundus appear to contribute in approximately equal proportions to the total amount of intraocular scatter.

Several investigators have sought to understand the relationship between glare luminance and glare angle (radial distance from the center of the source image). Indeed, the equivalent veiling luminance technique was originally used to establish the luminance of the glare source as a function of glare angle, θ.[23] Later, Stiles[39] extended the use to calculate the equivalent veiling luminance and then used this value to estimate the resultant reduction in image contrast on the retina. In general, a glare spread function can be expressed as follows:

$$\left[\frac{L_{veil}}{E_{glare}}\right] = f(\theta) = \frac{K}{\theta^{n}}$$

where

θ = the glare angle (degrees)
L_{veil} = the veiling glare luminance ($cd \cdot m^{-2}$),
E_{glare} = the glare illumination in the pupil plane (lux), and
K and n = constants.

The product of $E \cdot f(\theta)$ gives the glare luminance in $cd \cdot m^{-2}$.

In the earliest studies of Holladay[23] and Stiles,[39] $K = 10$ and $n = 2$. This yielded the so-called Stiles-Holladay formula ($L_{veil}/E_{glare} = 10/\theta^2$). Early studies measured glare spread from 5° to 25°. Subsequent studies over different angular domains have found slightly different values for K and n, the most notable being a steepening of the relationship for small glare angles (< 5°).

Estimates of the extent of laser glare must therefore begin with attention to how the laser light is distributed on the retina. The precise shape of the retinal distribution has been a topic of great concern in applied vision work related to veiling glare. There have been concerted efforts to quantify retinal distribution. Most notable among these are the works of Vos.[36,40–46] In a recent review, Vos published the Small Angle Disability Glare Equation,[21] with a validity domain for glare angles between 0.1° and 30°, which was developed for, and adopted by, the CIE.[47] The equation is expressed by relating the equivalent luminance of the veiling glare in $cd \cdot m^{-2}$, L_{veil} to the incident illumination from the glare source, E_{glare}. This describes a radially symmetric distribution of light on the retina as a function of angular distance, θ (in degrees), from the center of the source:

$$\left[\frac{L_{veil}}{E_{glare}}\right] = \frac{10}{\theta^{3}} + \left[1 + \left(\frac{Age}{62.5^{4}}\right)\right] \times \frac{5}{\theta^{2}}$$

This formula is valid for young healthy observers up to about 30 years of age. Variation in the glare spread function due to age (in the typical range for military personnel) is small. Figure 5-3 shows the relationship between glare angle and relative intensity based on a 30-year-old observer. Beyond approximately 0.1°, glare falls off rapidly with angle, and the shape of the curve is essentially that shown by Campbell and Gubisch,[35] characterized by a width (full-width, half-maximum) of <1 min of arc. Stray light from the cornea and lens decreases with increasing wavelength while that from fundus reflectance or *transillumination* of the iris and sclera increases with increasing wavelength.[48,49] As a consequence, stray light reaching the retina has little wavelength dependence.[50] There is an effect of pupil size, but this can be regarded as a second-order effect.[45] Intraocular scatter increases with age[40] as light scattering in the lens of the eye increases,[51] and the CIE function allows for this. Disability glare also increases in diseased eyes because opacities in the cornea and lens produce an increase in stray light.[52] In patients with early cataracts, increased lenticular light scattering has been shown to impair contrast sensitivity when the contrast sensitivity function is measured in the presence of a bright light source. This occurs even if visual acuity is unaffected.[53]

Extraocular Scatter. Target visibility through a transparency (eg, vehicle windscreens, visors, spectacles) depends on the way the transparency scatters

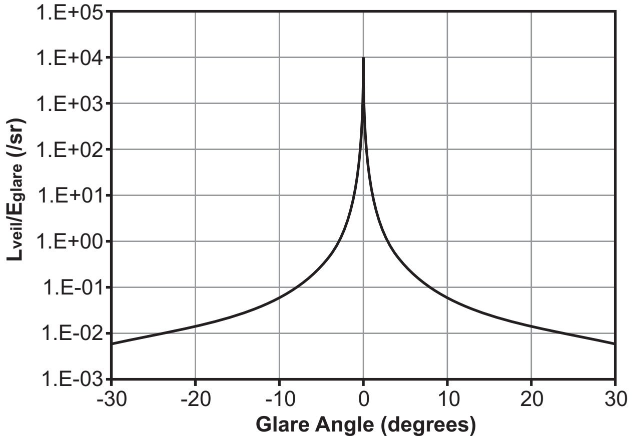

Figure 5-3. The CIE Small Angle Disability Glare Equation.

light.[54,55] The introduction of additional scattered light from a glare source can reduce visibility even further.[56,57] In this context, the atmosphere itself may also be regarded as a transparency that scatters light,[58] although recent studies with laser light have shown that this scatter may be significantly less than in the eye itself.

Quantitative data are rare concerning stray light scatter from typical optical transparencies. Allen[54] used a photographic technique to measure the scattering properties of car windscreens. To compare various windscreens, he used a veiling luminance index based on the veiling luminance factor at 5.3°, the value chosen to represent the typical geometry of approaching headlights in a driving situation where the index for the eye is 0.42. The value for car windscreens varied with windscreen condition. For a typical used windscreen, the value was about twice the value obtained for the eye. Allen also investigated the shape of the scatter curve from 3° to about 15°, and showed that it was qualitatively similar to that of the human eye. Although he attempted to study the effect of veiling luminance on visual performance in a driving situation, he did not attempt to correlate the glare index itself with performance.

Forward scatter from optical surfaces is often referred to as “haze,” but this term is used rather loosely in the literature. The American National Standard test method for haze and luminous transmittance of transparent plastics defines haze as the ratio of scattered light to the total amount of light emerging from an optical surface.[59] Acceptable levels for spectacles and windscreens are on the order of 1% to 6%. However, the relationship between haze and visual performance remains poorly understood.[55]

To determine the extent of laser-induced veiling glare on visual function, it is necessary to describe the distribution of light in the retinal image of the laser source (glare spread function). The shape of this distribution will depend on the scattering properties of the optical media through which the laser beam has passed. Scatter functions for the ocular media are well established, but those for extraocular scatter are not.

Visual Task Parameters

In broad terms, the parameters that make a visual task easier or more visible are those that will mitigate the effect of a glare source and reduce the time that is necessary for task performance to recover. These beneficial parameters include task luminance and the size and contrast of target stimuli. Generally, an increase in any of these parameters will tend to reduce both the immediate glare effect and subsequent recovery times.

Task Luminance. Hill and Chisum[60] studied the time taken to detect acuity gratings following flash exposure and demonstrated that display luminance level has a significant effect on detection time.[60] As display luminance is increased, recovery times are reduced (down to a minimum value). Because the target stimulus must be viewed through a fading afterimage, this effect arises from the competing effects of the afterimage and task parameters. Increasing display luminance serves to increase the contribution of the display to the retinal image. This improves stimulus contrast and hence visibility. At high display luminance, the upper limit for optimal viewing of the display is approached. There appears to be little difference in recovery time for different adapting luminance levels.

Although other studies have recognized the importance of task luminance as a factor in determining recovery times,[61,62] they have not gathered systematic data relevant to this parameter. Studies that have specifically adjusted display luminance as a primary independent variable[32,63,64] have found that as display luminance is reduced, recovery times increase at an increasing rate. This occurs down to a display luminance that represents the absolute threshold for the discrimination of the visual task.

Display luminance is an extremely important variable. Increasing the luminance of the display can significantly reduce recovery time. Of course, there will be a logical limit to this method of improvement because extreme increases may begin to interfere with the visual process itself.[22]

Target Size and Contrast. The size and contrast of a target stimulus can exert a profound effect on recovery time. Recovery times are longer for small acuity letters and low-contrast gratings.[31] In general, the greater the inherent difficulty of a visual task, the more time will be needed to recover the ability to perform that task. Recovery times for threshold stimuli are much longer than are those for suprathreshold stimuli.

Glare Recovery

Although the eye is extremely good at adapting to large changes in ambient illumination, adaptation problems can occur when the changes are large and occur over a short time period. When the eye is illuminated by an intense light source, visual effects do not terminate immediately after the light source is removed. Rather, they persist as transient loss of visual sensitivity for a definite time interval. In many situations, this effect may not cause any difficulties. However, serious problems may occur if the observer must perform a detailed visual task.

Although the exact mechanism of afterimage production is not fully understood, since an afterimage can be formed in an eye made temporarily anoxic by pressure on the globe, afterimages almost certainly originate in the photoreceptors.[65] The afterimage may result from the persistence of photoproducts that are produced by the bleaching of visual pigments.[66]

Afterimages persist following exposure of the eye to a bright flash. The afterimage appears immediately in the visual field as a bright area of the same size and shape as the original flash field. This may prevent the observer from perceiving detail in the same portion of the visual field. The afterimage will eventually fade, and normal visual function will then return. In this case, recovery time refers to the time interval between the flash and restoration of a given level of visual function.

As afterimages persist and fade, they undergo qualitative changes. If the eye is placed in darkness immediately after exposure, the afterimage appears initially as an image of the originating source itself. Its color and brightness will be similar to those of the stimulating source. On continued observation, color and brightness of the afterimage will begin to change. These changes are also apparent when the afterimage is viewed against an illuminated field.

Variations in the appearance of afterimages have given rise to a number of descriptive terms in the literature. *Positive afterimage* refers to a visual image that has the same relative brightness relations as the original stimulated field. The positive afterimage is believed to result from intense bleaching of retinal photopigment. This results in the imposition of a luminous veil on the visual image, thereby reducing its perceived contrast.[25,32,33]

A *negative afterimage* differs in that its brightness relation is opposite that of the original field. Afterimages may also be described as *homochromatic* or *complementary.* (For a detailed description of afterimages, see Brown.[67])

The interference in vision that results from afterimages has been referred to as *flash blindness*.[68] However, used in this way, the term is somewhat misleading. Rather than being blinded, the subject experiences a temporary reduction in the ability to see a visual stimulus in what is typically a limited portion of the visual field. A more appropriate description of this effect might be *transient localized visual desensitization*. Recovery of visual threshold has been tracked by matching the intensity of an external light to the perceived brightness of its afterimage.[32,33,69] The time that is needed for task performance recovery is usually less than the time it takes for an afterimage to disappear completely or for the eye to regain its preexposure level of sensitivity or adaptation. Under normal conditions, the eye operates at suprathreshold levels of adaptation. This means that an observer is often able to "see through" an afterimage sufficiently well to distinguish the required level of detail.

Due to the extreme but very necessary safety considerations involved with direct viewing of laser sources, there have been relatively few studies of laser effects on visual function. However, the nature of visual recovery has been studied extensively in human subjects using various types of noncoherent flash sources.[31–33,60,68,70–74] Studies using a variety of techniques (eg, fundus reflectometry and evoked potentials) have shown that there are two mechanisms responsible for the rapidly changing sensitivity of the eye following exposure to intense flashes: (1) the photochemical effect and (2) the neural effect. Because this chapter is primarily concerned with overall system response, the following discussion will be limited largely to psychophysical studies of afterimage recovery.

There have been many studies of the change in visual function that follows a small change in adapting luminance level at relatively low levels of light intensity. These effects are generally described as light and dark adaptation. In some respects, research into these changes can be regarded as precursors to the study of laser flash recovery, which involves exposure to high-intensity photic stimuli. The transient effects of intense light exposure have been studied to address three main areas of concern: (1) clinical application, (2) occupational hazards, and (3) basic visual function.

Clinical Studies

The most common clinical test involving intense light exposure is the *photostress recovery test* of macular function. Historically, this test employed an attenuated light coagulator and assessment of retinal response using a test, such as reading Landolt C's on the Goldmann-Weekers adaptometer.[75] Later studies have proposed the use of a simple penlight and Snellen chart.[76]

The purpose of the photostress test is to determine if the retina is diseased. The test imposes a full-field photic stress across the retina. Physiologically, the intense light source bleaches a significant proportion of the visual pigments, producing a transient state of insensitivity. Return of retinal sensitivity, and hence visual function, depends not only on neural mechanisms, but also on the regeneration of visual pigments in the retina.[14] Ocular disease that affects photoreceptor outer segments or pigment epithelium causes a delay in photopigment regeneration and leads to a slower recovery of visual function, whereas no such delay is observed for diseases of the optic tract. The photostress test has thus been useful as a means to determine whether reduced visual function is due to macular disease or optic neuropathy. Patients with maculopathies—such as central serous retinopathy, macular degeneration, or retinal detachment—show prolonged recovery times. Patients with optic neuritis, glaucoma, or retinal edema associated with contusion usually show normal recovery times.

Occupational Studies

In most occupations, overexposure to visible radiation is not a common risk factor. However, such accidents can occur in certain vocational situations. Early research in this area concentrated on problems arising from exposure to the flash of an atomic explosion. More recently, research has focused on the potential hazards to both military and civilian personnel from the uncontrolled use of lasers.[77,78] Lighting engineers have also shown some interest in problems associated with heterogeneous illumination in the workplace.[79]

Due to the practical nature of the problem, occupational studies are usually designed around everyday tasks. In general, these studies follow the same basic paradigm. The experimental subject is required to perform a realistic visual task. The subject is then exposed to a bright flash of light. Investigators then observe and measure the time required for the subject to return to a given criterion level of accuracy on the original task. Because dark adaptation is not of interest, viewing conditions are usually photopic, or at least mesopic, and hence involve cone function. Studies of this kind have documented recovery times ranging from as short as a few seconds to as long as 2 min.[61]

The luminous flux from a nuclear detonation is capable of producing retinal burns, flash blindness, and afterimages. Early studies established that retinal burns are unlikely at survival distances, although the flash exposure will still be considerable.[62] This conclusion led to a plethora of psychophysical studies. For obvious reasons, criterion tasks were designed to test vision in the aviation environment. Tasks involved reading key instruments or warning lights[61,72,80] and detection of grating pattern orientation.[60,70,73,74] Severin et al[75] even adapted the photostress recovery test to study this problem.[81] More recently, Wang et al measured recovery time as the time needed for a moving grating pattern to induce an optokinetic nystagmus.[82]

Basic Vision Research

The study of flash blindness and afterimages has attracted much interest in vision research. There may be some truth in the conclusion of Davson that "although they have attracted a lot of interest, little of fundamental value has emerged from their study."[7(p146)] Nevertheless, our understanding of the problem of afterimages has been improved by the application of basic principles of vision science. These principles also serve as a foundation for the present study. In particular, the concept of equivalent background luminance has been of great value to afterimage research.

Factors Affecting Visual Recovery Time

Researchers have used a variety of techniques to study afterimage recovery. For this reason, it is extremely difficult to compare results directly across studies. Recovery time depends on many variables, in particular task type and adapting flash parameters. The most important parameters of the adapting flash are flash intensity and duration, field size, and spectral content.

Flash Intensity and Duration

In terms of threshold effects on the eye, it is generally accepted that total energy is the determining variable for all exposures shorter than a critical duration of about 100 ms.[19] This is the Bunsen–Roscoe law of reciprocity, which states that the threshold remains the same as long as the product of stimulus intensity and duration is held constant. Bloch's law states that this same relationship applies to the intensity of visual sensation for exposures above the threshold.[19] It is unknown whether the same is true for the high-intensity and suprathreshold adaptation effects involved in the generation of prolonged afterimages.

Fry and Alpern[83] studied recovery using flash durations from 3 s to 3 ms. They concluded that recovery time was determined by total flash energy (ie, the product of adapting flash intensity and flash duration). However, the experimental task involved parafoveal (low) acuity and measures taken no earlier than 10 to 15 s after the flash exposure.

A similar study that used a foveal vision task reached the same conclusion; recovery time depended largely on total flash energy.[60] The greater the total flash energy, the more time was needed for subjects to detect the orientation of acuity gratings. At constant flash energy, recovery was unaffected by the duration of flashes ranging from 33 to 165 µs. However, the authors noted that recovery time was almost doubled when flash duration at constant energy was increased from 165 µs to 9.8 ms.

Miller[31] also studied the influence of flash energy on recovery times needed for observers to identify a dimly lit test letter. In this case, when the integrated retinal illuminance of the flash exposures was varied from 5.9 to 7.5 log troland-seconds (log td-s), visual recovery times varied from 14 to 109 s. However, Miller found no significant differences for flash durations from 40 µs to 1.4 ms. Later, Chisum[72] observed no systematic variation in recovery times for flash blindness exposures from 100 µs to 8.5 ms, and concluded that there exists a complex interaction between flash total luminance and duration. A strict reciprocity relationship may not hold for very short flashes, although the magnitude of the variation she observed was small (<10%).

A possible explanation for these apparently conflicting observations can be found by considering the work of Hagins,[84,85] who demonstrated that for flash durations of about <1 ms, it was not possible to bleach more than about half of the retinal photopigment. Williams[86] later hypothesized that this effect may be a consequence of unstable intermediate bleaching products that are isomerized back by the light itself.

Thus, there is reasonable evidence that, within certain limits, flash blindness recovery time is governed by total flash energy. Specifically, the greater the flash energy, the longer the recovery. The interaction between flash intensity and duration is complex, and strict reciprocity may not always apply. There remain some unresolved conflicts in the published body of experimental data.

Flash Source Size and Location

The visual angle subtended by the flash will determine the size of the retinal image of the source. This, in turn, will define the size of the resultant afterimage. The location of the afterimage is determined by the location of the flash source in the visual field. Although the location of the flash source itself is fixed in visual space, its afterimage is fixed in retinal space and will move with the eye.

Perhaps the most extensive and controlled study of the effect of flash field size and location on afterimage recovery was that performed by Chisum.[70] She measured the time to detect the orientation of high-contrast gratings that required foveal (20/60) acuity. Flash field sizes were 0.5°, 1°, 2°, 4°, 6°, 8°, and 10°. They were located on the optical axis or at the separation between the edge of the flash field and the optical axis (0.5°, 1.0°, 1.5°, and 2.0°). For the on-axis flashes, Chisum found that recovery times increased as the visual angle subtended by the adapting flash was increased from 0.5° to 2.0°. No further increase was seen as the visual angle was increased from 2° to 10°. Recovery times decreased as the flash field was moved away from the optical axis.

Most of these results can be explained by the degree of overlap with the fovea. The fovea subtends a visual angle on the order of 2°.[8] For flashes that subtend an angle less than 2°, some of the fovea will be unexposed. The unexposed portion of the fovea can be used to complete the visual task (ie, by looking around the afterimage). As field size approaches 2°, the unexposed area of the fovea becomes smaller, making it more difficult to avoid the afterimage. At 2°, the entire fovea is exposed, and recovery time will be unaffected by any additional increase in field size. For off-axis exposures, recovery times will also increase as the degree of overlap between the flash field and the fovea is increased.

Cushman[80] investigated the effect of flash field size using a criterion task that required subjects to read cockpit instruments. He tested flash field sizes of 1°, 3°, 5°, 10°, and 15°. He found that recovery time increased with increases in visual angle subtended by the source. However, the shape of this increase varied with the specific visual requirements of different cockpit instruments. In general, the most rapid changes (between 1° and 5°) were observed for instruments that required foveal vision. For less visually demanding instruments, changes were less dramatic, suggesting the involvement of parafoveal vision.

Therefore, if a central adapting flash subtends 2° or more, the entire fovea will be exposed. In this situation, it will not be possible to perform a foveal (ie, high-acuity) vision task by looking around the flash afterimage. Instead, the subject will have to wait until the afterimage has faded to the extent that it no longer prevents viewing of the task display. Flash fields smaller than 2° may spare some of the fovea, in which case the subject may be able to look around the afterimage. Relatively less demanding visual tasks may be performed by using parafoveal vision to avoid the afterimage.

Flash Spectral Content

In most of the studies described herein, investigators used a xenon flash lamp or some other conventional lamp as a light source. The light from these lamps has a broad spectrum and appears as white light to the observer. Very few studies have been done to test the possible effects of flash source spectrum (color) on visual recovery.

Wang et al[82] used narrow-band filters with a xenon flash tube to investigate the effects of the spectral content of the flash source. Using a recovery task that required a significant amount of dark adaptation, they found that variation in recovery time for equal energy flashes closely matched the scotopic spectral sensitivity (V_λ) curve. This study confirmed that the important factor in determining recovery time is flash total luminous energy (ie, radiant energy weighted by the appropriate spectral sensitivity curve).

Transient Effects of Laser Exposure

Although few human studies have been conducted to investigate visual recovery after exposure to nondamaging light from a laser source, safety concerns have limited most studies to the use of animal subjects. There are always ethical concerns about the use of animals in experimentation, and there are also well-known problems associated with extrapolating from animal models to human behavior. These problems notwithstanding, studies of this type have applied both behavioral and electrophysiological techniques. Although useful, both techniques present certain drawbacks.

Behavioral research techniques in this field are often cost-prohibitive because of the need for extensive subject training. Electrophysiological methods avoid this requirement, but suffer from a variety of other problems. For example, although signal characteristics may be closely correlated with the perception of the test stimulus, the nature of this relationship is not well understood. This raises questions concerning the extrapolation from electrophysiological data to visual performance or capability. In addition, electrophysiological response amplitudes are extremely low for foveal stimuli and visual stimuli presented at threshold.

Most studies of laser-induced transient visual deficits have used the monkey as a model. There is a strong similarity between the visual system of the monkey and that of human beings. Most such studies have applied electrophysiological techniques, such as electroretinography or visual-evoked potentials (VEPs), to track recovery. Although these studies probably monitor visual decrements related to prolonged afterimages, they are usually referred to as studies of flash blindness.

As with conventional light sources, the size of the laser-induced retinal afterimage depends on the size of the flash source. Collimated visible laser light entering the eye will be focused on the retina as an extremely small spot, approximately 0.1° (25 µm) in diameter.[87] Because visual disturbance is reduced if the afterimage subtends less than 2°, significant transient visual decrements are not expected as the result of laser exposure. Indeed, experiments using VEPs in rhesus monkeys have failed to demonstrate a flash effect from single Q-switched ruby (20 ns, 694 nm) laser exposures, even at doses that produced retinal lesions.[88] One could argue that this is because of an inefficient wavelength ($V_\lambda < 0.008$). However, similar results have been reported using much more efficient argon (250 ms, 514 nm, $V_\lambda = 0.61$) and Q-switched, frequency-doubled neodymium:YAG (yttrium aluminum garnet; 532 nm, $V_\lambda = 0.86$) lasers.

Previc et al[89,90] measured the amplitude of the steady-state VEP response following flashes from argon and doubled neodymium:YAG lasers. By expanding the beam to 3°, these investigators were able to show significant recovery times, measured as the latency of VEP amplitude reduction to preexposure baseline. The authors demonstrated several phenomena, all of which were consistent with flash recovery factors discussed previously in this chapter. Specifically, recovery time increased with flash energy and was dependent on test stimulus spatial frequency in a manner consistent with stimulus visibility as predicted by the baseline VEP. No effects were observed when the laser was allowed to form a minimal image on the retina, or if its exposure was not foveal. Finally, Previc et al[90] demonstrated reciprocity between flash intensity and duration; recovery times were similar for 20 ns and 100 ms flashes of constant energy.

In one of few behavioral studies, Rhodes and Garcia[91] trained monkeys to perform a visual detection task and exposed them to Q-switched laser flashes at 530, 694, and 1,060 nm at exposure levels up to the maximum permissible exposure.The beam was expanded to form a large (12.5°) spot centered on the fovea. Only the 530 nm wavelength produced a significant impairment of visual performance, an effect consistent with the spectral efficiency of laser wavelengths. Recovery was quickest for less demanding visual tasks and could be improved by increasing the contrast of the stimulus. No flash effect was observed when the image size was reduced to a minimal spot. Once again, all of these effects are consistent with those reported in human studies of flash recovery from conventional light sources.

These animal studies suffer from a distinct lack of quantitative information, so it would be very difficult to use their findings as a basis for predicting human visual performance effects. However, these findings are valuable because they

- confirm that recovery from laser exposure is qualitatively similar to that from conventional light,
- support the case that results from studies of recovery from conventional flash sources in human subjects that are often more quantitative, and
- can be used to predict the temporary effects of laser exposure.

SUMMARY

Laser glare and subsequent visual recovery depend on a number of variables. These include the parameters of the laser itself, the presence of intervening optical materials, and the visual task that must be performed. The extent of resulting visual decrement is not a simple binary function. For example, effects may manifest as a loss of high-acuity vision close to the center of the source image or as an increase in visual search time due to the persistence of a transient relative scotoma. The size of the scotoma will be relative to the parameters of the visual target; the scotoma will be much bigger for threshold stimuli than for suprathreshold stimuli. Although resulting visual deficits may be dangerous in very dynamic situations involving occupational tasks that require high levels of vigilance and fast response times (eg, piloting an aircraft or driving a vehicle), they may exert little or no practical effect on performance in other tasks that are more stable or pose less risk when compromised by temporarily slowed response.

It is not a trivial challenge to conduct an overall assessment of the transient effects of laser exposure on visual function and operator performance. It is not possible to derive a single estimate of the amount of laser energy that would be required to cause a problem in any particular situation. However, there are indirect estimation techniques that can be used to link the experimental data in a conceptual framework that can in turn be used to assess the transient effects of laser exposure on visual performance.[92,93] The conceptual framework expresses visual impairment in terms of object contrast degradation during and after laser exposure. The impact of laser exposure can then be assessed by using the degraded visual scene as input to a contrast-based model of visual perception.

In considering previous studies of the transient effects of intense light exposure, it is difficult to relate results across tasks and studies. To overcome this problem, it is vital to apply the equivalent luminance technique. This technique allows the expression of experimental findings in terms of an equivalent reduction in image contrast rather than as a reduction in visual sensitivity.[94] In addition, this technique simplifies the prediction of the effect of light exposure on visual performance by using the observation that detection probability can be related to image contrast.[95] The equivalent luminance technique also helps to relate the results of a dynamic situation (eg, instantaneous brightness of a fading afterimage) to a specific condition of steady-state adaptation.

To estimate the effect of laser glare on vision, one must begin by calculating the brightness distribution of light on the retina. This calculation must represent all of the scattering media for a given set of observation conditions. Glare spread equations for the eye, windscreens, and atmosphere can be used to construct a complete luminance profile of the laser source retinal image. For pulsed laser sources operating at frequencies > 30 Hz, glare effect can be taken as equivalent to a continuous wave source with the same time-averaged illumination.

To anticipate the effect of the glare source on the visual scene as a whole, the effective contrast (C_e) of elements in the visual scene can be reduced by adding the glare luminance profile on a point-by-point basis across the image of the scene. At any given glare angle, veil θ, a veiling glare of luminance, L, will be introduced, where L_{veil} is a function of glare angle. Target contrast is viewed with this veiling glare superimposed on the target and background. This will reduce the target contrast in a systematic way. For small, well-defined targets viewed against a uniform background, target contrast, C_{target}, is given by:

$$C_{target} = \frac{L_{background} - L_{target}}{L_{background}},$$

where

$L_{background}$ = luminance of the background and
L_{target} = luminance of the target.

Mathematically, glare luminance, L_{veil}, can be added to the background luminance and target luminance terms to give the reduced target contrast in the presence of glare:

$$C_{target} = \frac{\left(L_{background} + L_{veil}\right) - \left(L_{target} + L_{veil}\right)}{\left(L_{background} + L_{veil}\right)}$$

that reduces to:

$$C_{target} = \frac{L_{background} - L_{target}}{L_{background} + L_{veil}}.$$

Glare can be included in this formula by substituting the appropriate glare spread function, $E_{glare} \cdot f(\theta)$, for L_{veil}, as follows:

$$C_{target} = \frac{L_{background} - L_{target}}{L_{background} + E_{glare} \cdot f(\theta)}.$$

The glare spread function will depend on the scenario under consideration. It could represent only the eye or the eye and the atmosphere. It may need to include an intervening optical transparency. In addition, the scattering properties of any optical transparency will depend on the condition of the transparency itself. Contaminants such as dirt, scratching, mist, and rain will increase scatter considerably.[54]

When glare spread function has been determined, glare luminance can be added on a point-by-point basis across the retinal image of the visual scene. In this way, glare effect is expressed as a reduction in contrast of elements in the visual scene. The degraded image can then be used as the visual scene input to a contrast-based model of visual perception such as ORACLE[96] or VIDEM.[95] These models are used to assess a variety of visual performance factors and could additionally be used to predict the effect of a glare source on vision.

If a light source is sufficiently intense, exposure may result in flash blindness and subsequent formationof an afterimage. This chapter did not specifically consider short duration flash blindness in the context of a full-field loss of visual function and visual disorientation. Indeed, many so-called studies of flash blindness are actually studies of afterimage recovery. The body of available literature serves to demonstrate how an afterimage may impair visual performance, especially for high-acuity visual tasks. The afterimage acts as a relative scotoma. Although the afterimage improves rapidly with time, even a small, short-lived scotoma may be troublesome in some situations. Studies involving simulated scotomas have shown that to impair visual search time for a visual target subtending 10 min of arc, the area affected by the afterimage must be foveal and must subtend an angle greater than 2°. For more visually demanding tasks, search times may be increased with a smaller scotoma.[97]

The degraded visual scene can be used as input to a contrast-based model of visual performance. However, it is necessary for such assessments to include the time element that represents fading of the afterimage. An additional question is whether the reciprocity of intensity (Bloch's law) holds for Q-switched lasers whereby energy can be deposited in nanoseconds. Brindley[98] has demonstrated that reciprocity holds for the threshold detection of low-luminance flashes shorter than 1 ms. In addition, Previc et al[89,90] showed that visual deficits after equal total energy flashes of 100 ms and 20 ns duration followed a similar time course. As a first approximation, this evidence would seem to support the working assumption that Bloch's law holds even with very short flashes.

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