N69-12436

2. LIGHT ENVIRONMENT

A. VISIBLE LIGHT

Visible light is that band of the electromagnetic spectrum from 380 to 750 millimicrons or nanometers (nm), capable of stimulating the photoreceptors of the eye thereby producing a sensation called vision. The physical phenomenon of light may be viewed in two different ways: as energy quanta (photons) or as waves passing through a medium. The interaction of visible light with biological systems can be interpreted as a manifestation of both viewpoints.

Characteristics of the Human Sensor

Light is sensed by the retinal photon receptors of the eye after passing along the optical path as seen in Figure 2-1. Light rays reflected from an object in the external world pass through the cornea at the front of the eye, through the liquid (aqueous humor) in the anterior chamber directly behind the cornea, then through the lens and vitreous humor onto the retina. Data on the spectral transmission of the ocular media are available (63).

The rods and cones of the retina transduce the light into neuro-electrical phenomena. The neural elements of the retina are gathered into the optic nerve at the blind spot and pass by discrete pathways to the highest visual center in the brain in the occipital cortex.

The human visual system is a very versatile one, with ample capabilities of adaptation to a variety of environmental changes. This versatility dictates that many variables in the physical and biological environment must be assessed in evaluating human standards for visual performance (117).

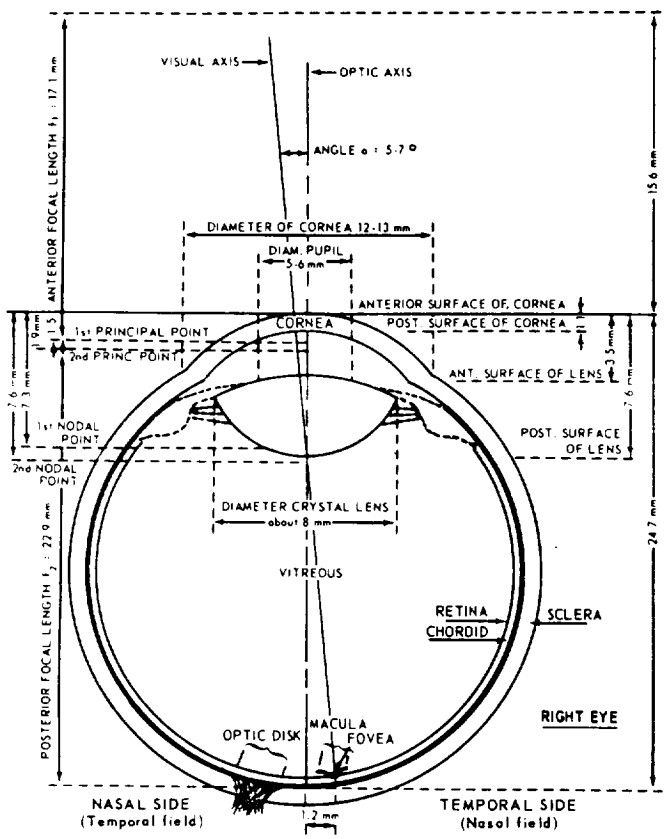
Nomenclature

A summary of terms and symbols commonly used in physiological optics is presented in Table 2-2.

Figure 2-3 lists and graphically demonstrates the relationship between intensity and illuminance units frequently used in the literature. Table 2-4 is a nomograph allowing conversion of the many equivalent units of luminance in common use. Table 2-5 allows conversion of other parameters.

The new unit of luminous intensity is the candela or new candle. A candela is equal to 1/60th of the luminous intensity of 1 cm^2 of a blackbody surface at the solidification point of platinum and represents about .981 candles.

a.



b.

Constant	Eye Area or Measurement	
Refractive index	Cornea	1.37
	Aqueous humor	1.33
	Lens capsule	1.38*
	Outer cortex, lens	
	Anterior cortex, lens	
	Posterior cortex, lens	
	Center, lens	1.41
	Calculated total index	1.41
	Vitreous body	1.33
Radius of curvature, mm	Cornea	7.7
	Anterior surface, lens	9.2-12.2
	Posterior surface, lens	5.4-7.1
Distance from cornea, mm	Post. surface, cornea	1.2
	Ant. surface, lens	3.5
	Post. surface, lens	7.6
	Retina	24.8
Focal distance, mm	Anterior focal length	17.1 [14.2]**
	Posterior focal length	22.8 [18.9]
Position of cardinal points measured from corneal surface, mm	1. Focus	-15.7 [-12.4]
	2. Focus	24.4 [21.0]
	1. Principal point	1.5 [1.8]
	2. Principal point	1.9 [2.1]
	1. Nodal point	7.3 [6.5]
	2. Nodal point	7.6 [6.8]
Diameter, mm	Optic disk	2-5
	Macula	1-3
	Fovea	1.5
Depth, mm	Anterior chamber	2.7-4.2

*Cortex of lens and its capsule
**Values in brackets refer to state of maximum accommodation

The diagram and table give dimensions and optical constants of the human eye. Values in brackets shown in the table refer to state of maximum accommodation. The drawing is a cross section of the right eye from above.

The horizontal and vertical diameters of the eyeball are 24.0 and 23.5 mm, respectively. The optic disk, or blind spot, is about 15 degrees to the nasal side of the center of the retina and about 1.5 degrees below the horizontal meridian.

Figure 2-1

Schematic and Optical Constants of the Eyeball

(After White [446] Adapted from Spector, ed.[394])

Table 2-2

Summary of Terms and Symbols Commonly Used in Optics

Term	Symbol	Units
	LIGHT	
Velocity in vacuo	c	2.99776×10^{10} cm/sec
Frequency	ν	cycles/sec or Hertz
Wavelength	λ	millimicrons or nanometers
Velocity in any medium m	V_m	cm/sec
Index of refraction	n	ratio $n = c/V_m$
Temperature	T	degrees absolute, K
Work	W	joule = 10^7 ergs = 10^7 dyne-cm
Energy (see end note)	E or U	joule = 10^7 ergs = 10^7 dyne-cm
Power	P	watt = joule/sec
Planck's constant	h	6.624×10^{-27} erg-sec
	RADIOMETRY	
Radiant energy (see end note)	E or U	joule
Radiant flux	P	watt = joule/sec
Unit solid angle	ω	steradian = $1/4\pi$ sphere
Radiant intensity	J	watt/ω
Irradiance	H	watt/m^2
Radiance	N	watt/ω/m^2
	PHOTOMETRY	
Luminous flux	F	lumen = $\frac{1}{685}$ watt at $\lambda = 555$ mμ
Luminous intensity (candlepower)	I	lumen/ω = candle
Illuminance	E	lumen/m^2 = lux = meter-candle = 0.0929 ft-candle
Luminance	B	lumen/ω/m^2 = candle/m^2 = 0.3142 millilambert = 0.2919foot-lambert
Retinal illuminance	$L \cdot S$	troland (uncorrected for Stiles-Crawford effect) = luminance of 1 candle/m^2 on a surface viewed through an artificial pupil of area $S = 1$ mm^2 or $= \frac{1}{\text{Brightness in millilamberts}} \times \frac{10}{\pi} \times \text{Area in mm}^2$

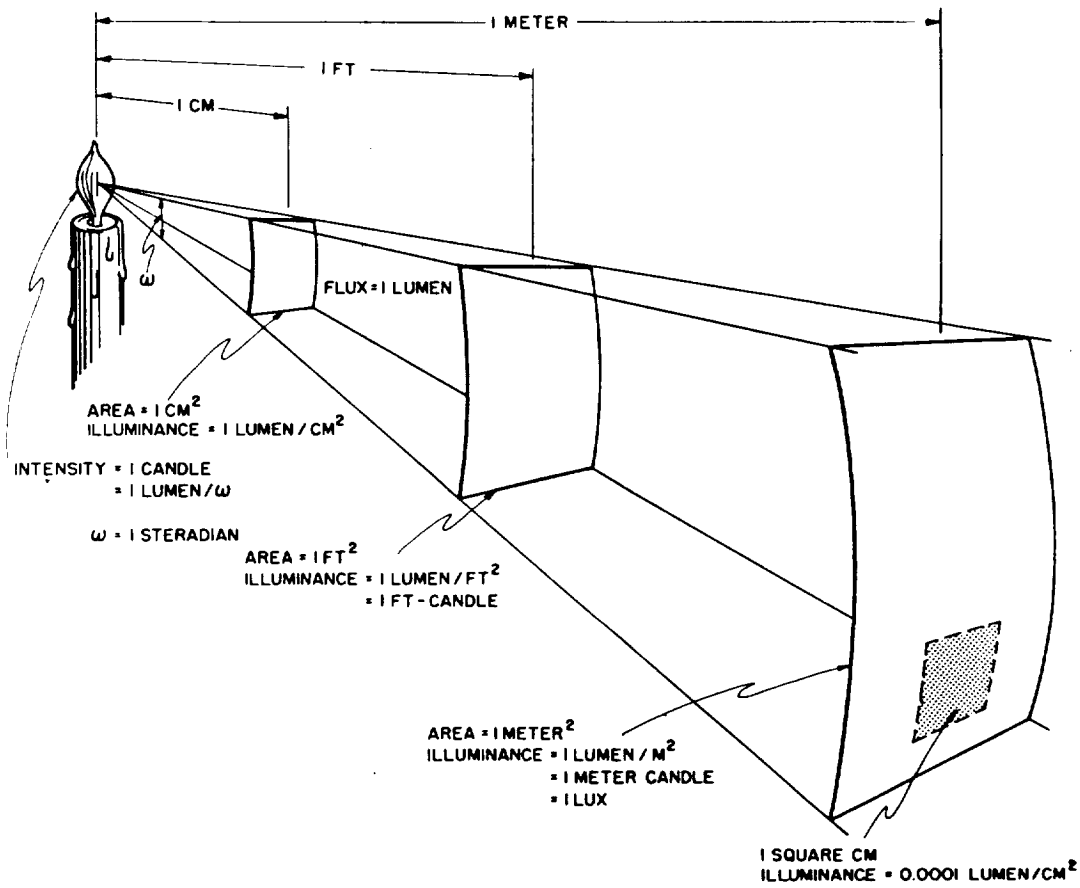
Table 2-2 Continued

COLORIMETRY

Transmittance	T_λ	Ratio $T_\lambda = P_{\lambda_T}/P_{\lambda_0}$, where P_{λ_0} is incident flux and P_{λ_T} is transmitted flux at wavelength λ.
Reflectance	R_λ	Ratio $R_\lambda = P_{\lambda_R}/P_{\lambda_0}$, where P_{λ_R} is reflected flux at wavelength λ.
Relative scotopic luminosity (also called relative scotopic luminous efficiency; formerly called scotopic visibility; also infrequently and informally, spectral sensitivity.)	V_λ'	Ratio of luminous efficiency of light at wavelength λ for standard observer at low levels of luminance to luminous efficiency maximum at 505 mμ.
Relative photopic luminosity (also called relative photopic luminous efficiency; formerly called photopic visibility; also infrequently and informally, spectral sensitivity.)	V_λ	Ratio of luminous efficiency of light at wavelength λ for standard observer at high levels of luminance to luminous efficiency maximum at 555 mμ.
Luminous flux	F	lumens $= 685 \int_0^\infty P_\lambda T_\lambda V_\lambda \, d_\lambda$ (for transmitted light) lumens $= 685 \int_0^\infty P_\lambda R_\lambda V_\lambda \, d_\lambda$ (for reflected light)
Dominant wavelength (spectral centroid)	λ_c	$\lambda_c = \dfrac{\int_{\lambda=0}^\infty P_\lambda T_\lambda V_\lambda \lambda d_\lambda}{\int_{\lambda=0}^\infty P_\lambda T_\lambda V_\lambda \, d\lambda}$ (for transmitted light) $= \dfrac{\int_{\lambda=0}^\infty P_\lambda R_\lambda V_\lambda \lambda d\lambda}{\int_{\lambda=0}^\infty P_\lambda R_\lambda V_\lambda \, d\lambda}$ (for reflected light)
Tristimulus functions for the standard observer. Also called distribution coefficients.	$\bar{x}, \bar{y}, \bar{z}$	Amounts of the three CIE primaries required to match a unit amount of energy at each wavelength.
Tristimulus values	X, Y, Z	Sums of weighted values from spectral energy data at all wavelengths.
Chromaticity coefficients	x, y, z	$x = \dfrac{X}{X+Y+Z}$ $y = \dfrac{Y}{X+Y+Z}$ $z = \dfrac{Z}{X+Y+Z}$

(Adapted from Graham[177])

Intensity (I)	1 lumen /steradian = 1 candle = 1 candle power = 1.02 candelas
Illuminance (E)	lumens/cm^2 1 lumen/m^2 = 1 meter candle = 1 lux 1 lumen/ft^2 = 1 ft-candle (ft-c)
Luminous Emittance (L)	lumens/cm^2 lumens/m^2 lumens/ft^2
Luminance (B)	lumens/steradian/m^2 (or cm^2) lamberts (L) = millilamberts (mL) $\times 10^3$ = microlamberts (μL) $\times 10^6$ for a perfectly diffusing surface, 1 lambert = $1/\pi$ candles/cm^2.foot-lambert (ft-L) = 1.076 mL



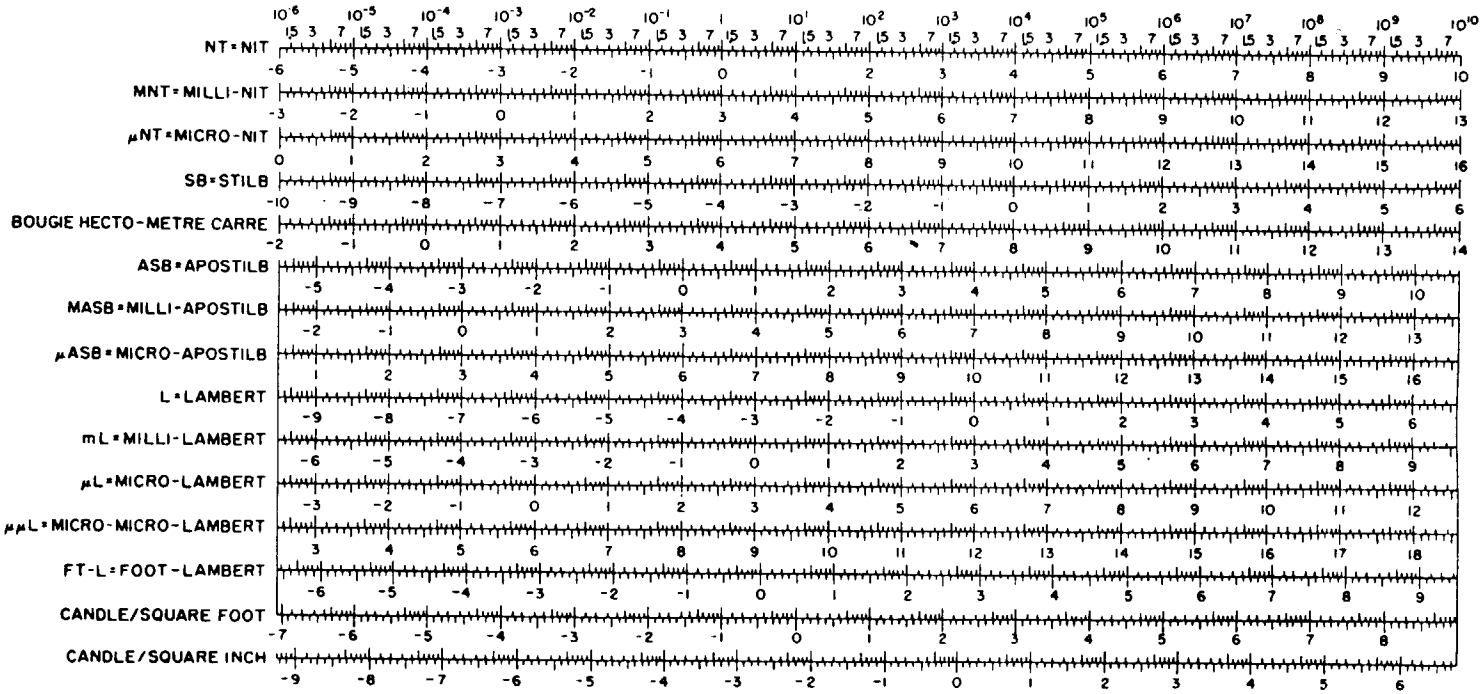
Relationships Between Intensity Units of Source and Illuminance Units on Surfaces at Various Distances

Figure 2-3

(After Sears [375])

Table 2-4

Nomograph of Equivalent Values of Commonly Used Units of Luminance. Below Each Bar Logarithmic Units and their Subdivisions Are Given. Above the Nit Bar Natural Figures and Subdivisions Are Given. Above Each Bar Subdivisions for Natural Figures Are Given.



(After Rose[363])

Table 2-5

CONVERSION FACTORS

To convert any quantity listed in the left-most column to any quantity listed to the right, multiply by the factor shown.

Luminous Flux
(Intensity of a Source)

	Candle-power	Lumens	Watts	Ergs/second
Candlepower	1	4π	0.005882π (at 555mμ**)	$5.882\pi \times 10^4$ (at 555mμ**)
Lumens	$\frac{1}{4\pi}$	1	0.001471 (at 555mμ**)	1.471×10^4 (at 555mμ**)
Watts	$\frac{170}{\pi}$ (at 555mμ*)	680 (at 555mμ*)	1	10^7
Ergs/second	$\frac{170}{\pi} \times 10^{-7}$ (at 555mμ*)	680×10^{-7} (at 555mμ*)	10^{-7}	1

Illuminance
(Illumination incident upon a surface)

	Foot-candles	Meter-candles	Lumens/ft²	Lumens meter²
Footcandles	1	10.764	1	10.764
Meter-candles	0.0929	1	0.0929	1
Lumens/ft²	1	10.764	1	10.764
Lumens/meter²	0.0929	1	0.0929	1

Luminance
(Surface brightness or reflected light)

	Candles/ foot²	Candles/ meter²	Footlamberts	Apostilbs***	Lamberts (Lumens/cm²)
Candles/foot²	1	10.764	π	10.764π	$\frac{\pi}{929}$
Candles/meter²	0.0929	1	0.0929π	π	$\pi \times 10^{-4}$
Footlamberts	$\frac{1}{\pi}$	$\frac{10.764}{\pi}$	1	10.764	10.764×10^{-4}
Apostilbs***	$\frac{0.0929}{\pi}$	$\frac{1}{\pi}$	0.0929	1	10^{-4}
Lamberts (Lumens/cm²)	$\frac{929}{\pi}$	$\frac{10^4}{\pi}$	929	10^4	1

Quantity of Energy Received By a Surface

	Meter-candle-Seconds	Footcandle-Seconds	Ergs/cm²	Watt-seconds/cm² or Joules/cm²
Meter-candle-Seconds	1	0.0929	1.471 (at 555mμ**)	1.471×10^{-7} (at 555mμ**)
Footcandle-Seconds	10.764	1	15.83 (at 555mμ**)	15.83×10^{-7} (at 555mμ**)
Ergs/cm²	0.680 (at 555mμ*)	0.0632 (at 555mμ*)	1	10^{-7}
Watt-seconds/cm² or Joules/cm²	6.80×10^6 (at 555mμ*)	6.32×10^5 (at 555mμ*)	10^7	1

Quantity of Energy Emitted by a Source

	Lumen-Seconds	Candle-power-Seconds	Watt-seconds or Joules	Ergs
Lumen-Seconds	1	$\frac{1}{4\pi}$	0.001471 (at 555mμ**)	0.001471×10^{-7} (at 555mμ**)
Candlepower-Seconds	4π	1	0.005882 (at 555mμ**)	0.005882×10^{-7} (at 555mμ**)
Watt-seconds or Joules	680 (at 555mμ*)	$\frac{170}{\pi}$ (at 555mμ*)	1	10^{-7}
Ergs	680×10^7 (at 555mμ*)	170×10^7 (at 555mμ*)	10^7	1

*True only for monochromatic light at 555mμ. For other wavelengths in the visible region, multiply by the relative visibility factor for that wavelength.

**True only for monochromatic light at 555mμ. For other wavelengths in the visible region, divide by the visibility factor for that wavelength.

***Defined as 1 lumen per meter²; occasionally incorrectly called meter-lambert.

(Adapted by Taylor and Silverman[404] from Eastman Kodak[136])

The Light Environment

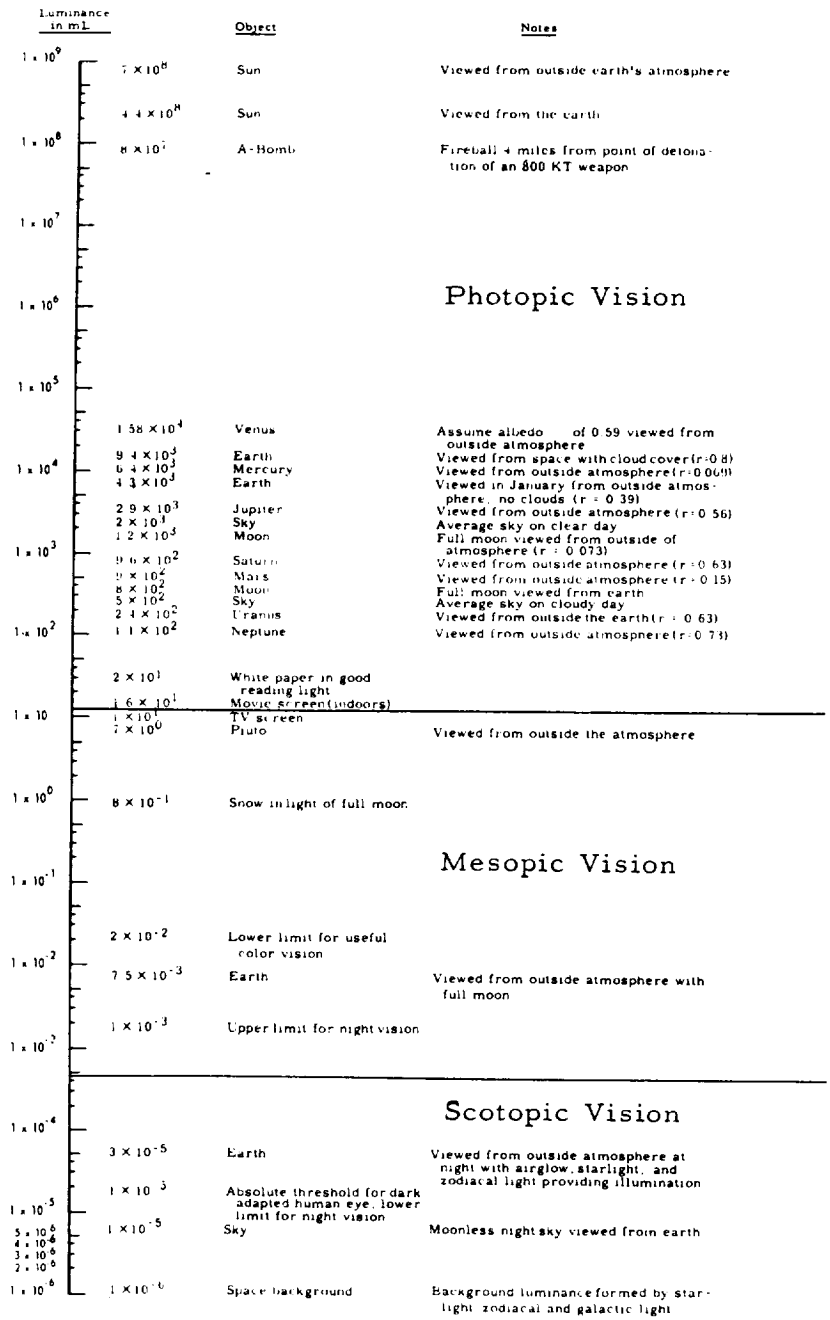
In order to define the visual factors in space operations, a knowledge of the physical light environment is required (16, 244, 354).

Table 2-6 covers the characteristic luminance on Earth and space. Photopic vision refers to that vision in which the cones of the eye are the prime receptors. In scotopic vision, the rods are the prime receptors, and in mesopic vision, both retinal elements are used.

Figure 2-7 represents the daily variation of natural illumination on Earth. More detailed coverage of these data, including haze effects, is available (73, 132). The illuminance of the Sun just outside the Earth's atmosphere is approximately 12,700 foot-candles.

Table 2-8 covers the luminance of some pertinent astronomical phenonena. A more detailed evaluation of the night sky is available (352).

Figure 2-9 presents the illuminance of stars for each stellar visual magnitude and threshold stellar magnitude as a function of background luminance. Table 2-9a is based on 3.90×10^{-8} foot candles as the illuminance of a second magnitude star (459). The stars are isometrically point sources and the light from the Sun, Moon, and other extended sources is collimated to within 32 minutes of arc of the subtended angle of the source. There appears to be some confusion in the literature as to the size of the source which can be considered a point source to the eye. The psychophysical definition of a point source is given by Ricco's law which states that the product of the threshold contrast and the solid angle subtended by the target are constant for any given adaptation level. Figure 2-18 shows the maximum visual angle for a point source at different background luminances. Note that the angle increases with decreasing background luminance. In the debriefings of all astronauts of the Gemini and Mercury space flights, there has been a continual insistence by the astronauts that "stars cannot be seen in the daytime," the only qualification of this statement being that planets and the Moon or perhaps the brightest stars (for example, Sirius) could be seen. This may have been due to the ambient light in the space cabin contributed by the spacecraft corona (see Figure 2-12) , the density of the window or scattered window light (319). However, the intensity of ocular scattering may also be sufficient by itself to make impossible the observation of first-magnitude stars if the level of illumination on the face of the observer exceeds about 1000 lux (100 ft-c) (15). "Unless the viewing window of the space capsule is protected by a conical sunshade it will be difficult to reduce the interior illumination below this critical figure, even if the other window is obscured by a blind, as 1000 lux is only about 1 percent of the outdoor daylight level. This fogging effect of ocular scattering is often experienced by city-dwelling astronomers who find that it is impossible to see the Milky Way within about 90 degrees of the direction of a single street lamp that produces an ambient light level only about 0.01 percent that of daylight. That ocular scattering, rather than atmospheric scattering, produces the observed loss of contrast in the visual image of the sky can be shown by stepping into the shadow of the lamppost."



This enormous range of luminances is based on a solar illuminance of 12,700 Ft-c. A uniformly diffusing sphere at the earth's distance from the Sun would have a luminance of 13,655 mL and the apparent luminances of the Su, Earth, Moon, Venus, and Jupiter have been recalculated on that basis. Albedo (r) as used in this figure is the ratio of the incident collimated light in a planetary body or spherical object to the light reflected and collected over 4π steradians and is considered to be invariant with wavelength. Only Jupiter and Venus are large enough to be characterized by their surface brightness.

Figure 2-6

Characteristic Luminance on Earth and in Space

(Modified from White[446])

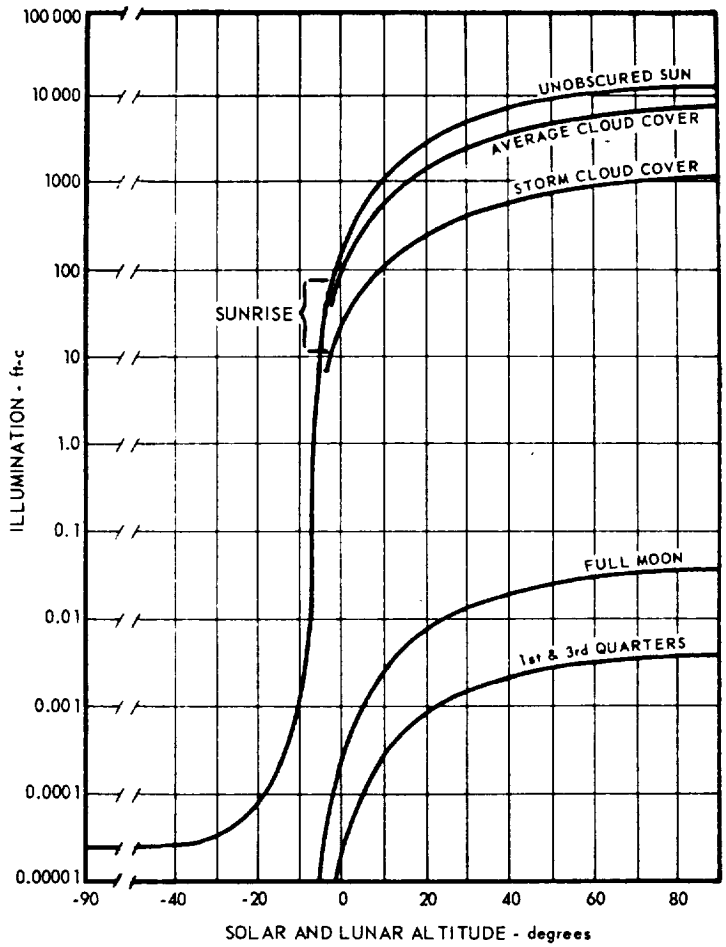


Figure 2-7

Range of Natural Illumination Levels on Earth.

This Graph Shows the Range of Natural Illumination on Earth from the Sun and the Moon, as the Values Increase from Minimum Before Sun- or Moonrise to Maximum at the Zenith.

(After White[446]) Adapted from Brown[73])

Table 2-8

Luminance of Astronomical Phenomena as Viewed from Earth

Phenomenon	Luminance, foot-lamberts
Milky Way, dimmest region, near Perseus	2.9×10^{-5}
Gegenschein	4.6×10^{-5}
Visible night glow (zenith)	5.8×10^{-1}
Aurora IBC-I	$\sim6\times10^{-5}$
Milky Way brightest region, near Carina	1.1×10^{-4}
Zodiacal light (30° elongation)	3.5×10^{-4}
Visible night glow (edge-on)	1.7×10^{-3}
Great Orion nebula M42	1.6×10^{-2}
Full moon	1.2×10^{3}
Fluorescent lamp 4500 white	1.2×10^{3}

(Adapted from Dunkelman[128] by Allen[12])

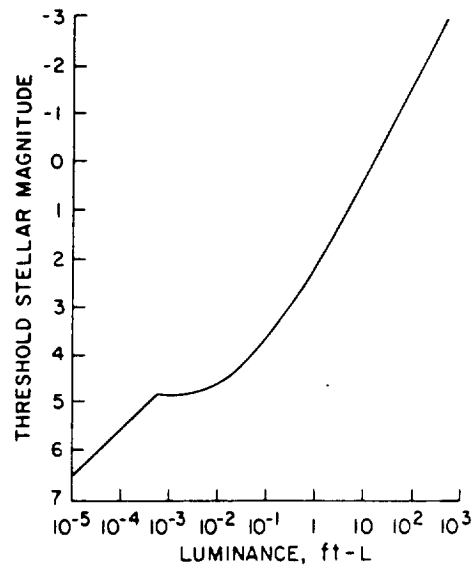
Figure 2-9

Visibility of the Stars

(After Allen[12])

M_V	Illuminance (ft-cd)
-2	1.55×10^{-6}
-1	6.18×10^{-7}
0	2.46×10^{-7}
1	9.79×10^{-8}
2	3.90×10^{-8}
3	1.55×10^{-8}
4	6.18×10^{-9}
5	2.46×10^{-9}
6	9.79×10^{-10}
7	3.89×10^{-10}
8	1.55×10^{-10}

a. Stellar Visual Magnitude and Illuminance



b. Star Visibility Versus Background Luminance

Figure 2-10 summarizes pertinent parameters of the visual environment of space. Extensive reviews of the photometry of the Moon and planets are available (27, 244, 393). The reflectance of the Earth as viewed from outside the atmosphere has a greater range than the range of observed reflectance from all other planets and satellites. The reflectance of the Earth varies from 0.03 for large bodies of water to 0.85 for cloud cover. More detailed reflectance data for local areas on Earth are available (132). Other solar system reflectance values range from 0.07 for Mercury to 0.7 for Neptune. Optical data needed for predicting the view of Earth, Moon and planets from space have been presented (351).

Optical properties of the Moon pertinent to human visual function have received recent review (12, 244, 316, 364, 410). The natural illumination of the lunar surface comes from direct sunlight; reflected sunlight primarily from Earth, but in some small degree from other planets in the solar system; and from starlight. The intensity of the sunlight falling on the lunar surface is about 1.4 times that which reaches the surface of the Earth or 12,700 foot-candles. The solar disc has a luminance of 6.4×10^8 ft L subtending a visual angle of 0.5 degrees. Data are available on the mean illumination of the Moon by different phases of crescent Earth (316).

From telescopic data, the rough and broken lunar surfaces (craterwalls) reflect from 20 to 30% of the incident light while the smooth and darker layers of the maria between 6 and 7% (253, 328, 402). The Moon has a highly directional reflectance. The variation of reflectance with phase angles is shown

Table 2-10

Primary Parameters of the Visual Environment of Space

(After Jones et al[241])

	90° Solar Illumination	Surface Reflectance*	Mean Atmos. Transmission
Earth (Night illumination with full moon = 0.04 ft-c)	10,800 ft-c	Ocean .03 Ground .15 Snow .80	.70-.80**
EVA (Earth Orbit)	12,700 ft-c	Aluminum .55 Dark Paint .10 White Paint .80	1.00
Moon (Full earth = 1.25 ft-c 30° phase = 0.80 ft-c 90° phase = 0.26 ft-c)	12,700 ft-c	Maria .07 Crater Wall .20	1.00
Mars	7,600 ft-c	Maria .17 Continents .18	.80

*Lunar reflectances from references (105)
Mars reflectances from reference (193)
**Function of diameter and distribution of scattering particles.

in Figure 2-11. The average normal albedo of the lunar surface in the vicinity of the Surveyor spacecraft was about 6%. The range of reflectance of local lunar areas is even greater than 0.06 to 0.30 (12, 112, 316). The highest luminances (not in shadow) may vary from 0.08 to 0.42 of a white target in full sunlight on the surface of the Earth. "Limb darkening" on the lunar surface decreases the lower value to approximately 0.003. Thus, the apparent luminance varies from 0.003 to 0.40 of the luminance of the hypothetical white target, or a range approximately 100 to 1. In comparison, the range of luminance on Earth outdoors on a partially cloudy day, with part of the landscape in full sunlight and part in cloud shadow, can be more than 1000 to 1.

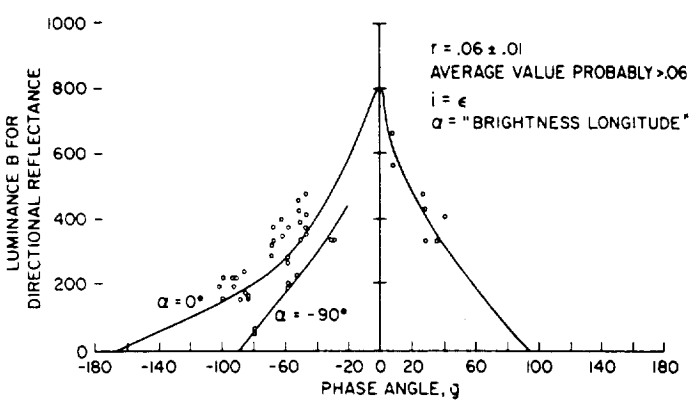


Figure 2-11

Lunar Reflectance Values

The Open Circles Are the Data Obtained from Preliminary Analysis of Surveyor I Data. The Solid Lunar Curve is the Federetz Curve Obtained from Telescopic Observations from the Earth

(From Preliminary USGS/JPL Data[12,227,410])

It thus appears that brighter areas may have an apparent luminance in excess of 1000 ft-L (410). Owing to the lack of atmospheric scattering, it may be expected that the deepest shadows will approach effectively zero luminance (10^{-6} ft-L or less). Without sun, illumination levels are likely

to be in the neighborhood of 10 ft-C for full Earth conditions, with a resulting maximum luminance of something over 1 ft-L, but decreasing markedly with Earth phase angle. Starshine alone is estimated to produce about 3×10^{-5} ft-C, and, unlike Earth and Sun, of a diffuse rather than unidirectional nature, so that a general average luminance might approach 10^{-5} ft-L without the severe shadow-casting effects just noted. Absence of atmospheric haze on the lunar surface may be considered in visual range determinations, although dust may be a factor (132, 144, 353).

In the vicinity of the spacecraft in orbit or on the lunar or planetary surface, the "spacecraft corona effect" must be included in the light path (319). This results from a cloud of particles traveling with the spacecraft. The surface brightness of the corona, in sunlight, has been computed as a function of the mass ejection rate of particulate matter from the spacecraft (Figure 2-12). This may have contributed to the inability of the astronauts to see stars previously predicted as visible (see Figure 2-9 and discussion).

Recommendations for dim light photography, photographic tracking, and visual observations of space phenomena from manned spacecraft are available (120, 127).

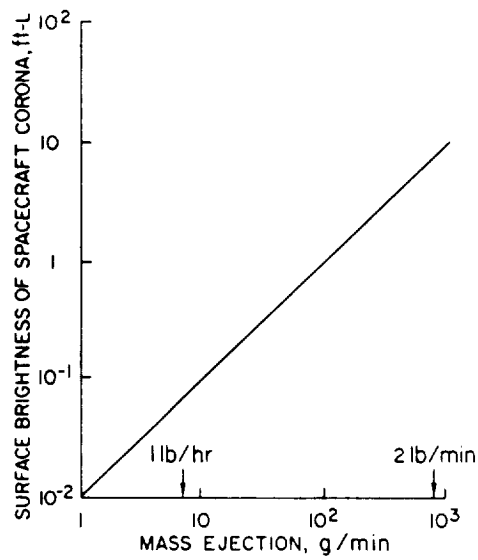


Figure 2-12

Surface Brightness of Spacecraft Corona Versus Mass Ejection Rate in Space.

(After Ney and Huch [319])

Visual Performance and Visibility

The interactions of the visible light environment with the eye should be considered as a dynamic and continuously changing process. The dynamism of this operation applies to every situation - to a change in the environment, in the sense organ, or in both. It is very important to consider all psychophysiological cues that will optimize visual function (462).

An excellent detailed review of physiological optics has recently been published and is recommended for definitive data on the more esoteric aspects of this subject (177).

The determination of visibility in any environment requires basic information of human visual performance. Much of the basic data to be presented were determined as special test cases with circular targets of known position in a uniformly luminous background using binocular vision. To such data must be added case-specific variables of luminous environment, unknown location, movement, variable duration of viewing, environmental stress, and psychological factors to permit accurate estimation of visibility in field or space conditions. Many of these variables have been covered in a recent review of visibility (132).

Table 2-13 summarizes some of the major physiological and physical factors which determine visual performance. In the present discussion, these variables will be covered in their more general aspects. In section 3, those conditions sensitive to specific aspects of space operations will be selected for discussion.

Table 2-13

Variables That Must Be Kept Constant or Carefully Controlled When Measuring Some of the Principal Kinds of Visual Performance

Type of Visual Performance	Variables to Be Controlled												
	Level of Illumination	Region of Retina Stimulated	Stimulus Size	Stimulus Color	Contrast Between Test Object and Background	Adaptive State of the Eye	Duration of Exposure	Distance at Which Measured	Number of Cues Available	Movement	Other Objects in Field	Monocular vs. Binocular	Stimulus Shape
Visual Acuity	X	X	(MV)*	X	X	X	X	X		X			X
Depth Discrimination	X		X	X	X	X	X	X	X	X	X	X	
Movement Discrimination	X	X	X	X	X	X	X	X		(MV)*	X		X
Flicker Discrimination	X	X	X	X	X	X	X						
Brightness Discrimination	X	X	X	X	(MV)*	X	X			X		X	X
Brightness Sensitivity		X	X	X	(MV)*	X	X			X			X
Color Discrimination	X	X	X	(MV)*	X	X	X	X	X		X		

*Variable being measured

(After Wulfeck et al[462])

Visual Acuity

Visual acuity is an important limiting factor in all human detection, target recongition, or other visual tasks. Acuity, like many other visual capacities, is measured and defined in terms of thresholds. One type of visual threshold is a value determined statistically at which there is a 50% probability of the target being seen. In most practical situations a higher probability of seeing, such as 95 or 100% is required. The general relation between threshold size and probability of detection is an ogive function of the general simplified form shown in Figure 2-14. This curve covers a specific test case and should be used only as a very rough guide for estimating the relationship between visual angle and probability of detection under different conditions. It can be seen that doubling the visual angle for 50% probability of detection should give almost 100% detection if the location of the object is known. Threshold data are usually based on the 50% probability of detection. As a rough rule of thumb, these visual angle values should be doubled to give near 100% threshold values. More specific conversion factors for near 100% probabilities are available (52).

There are several ways in which visual acuity has been defined and measured, each of which has significance for detection and recognition of detail. These are defined in Figure 2-15.

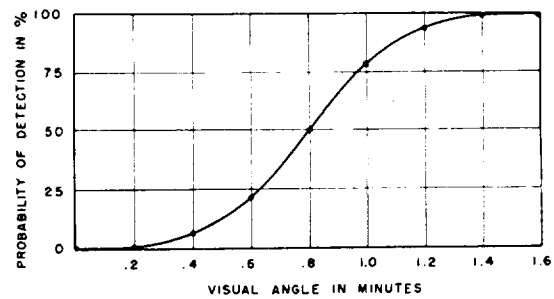


Figure 2-14

An Example of Probability of Detection at Different Visual Angles for a Specific Test Case. (After Baker and Grether[25] Adapted from Blackwell[49])

The luminance contrast between target and background determines the minimum visual angle which can be detected. Luminance contrast is a measure of how much target luminance (B_t) differs from background luminance (B_b). The equation for obtaining contrast is:

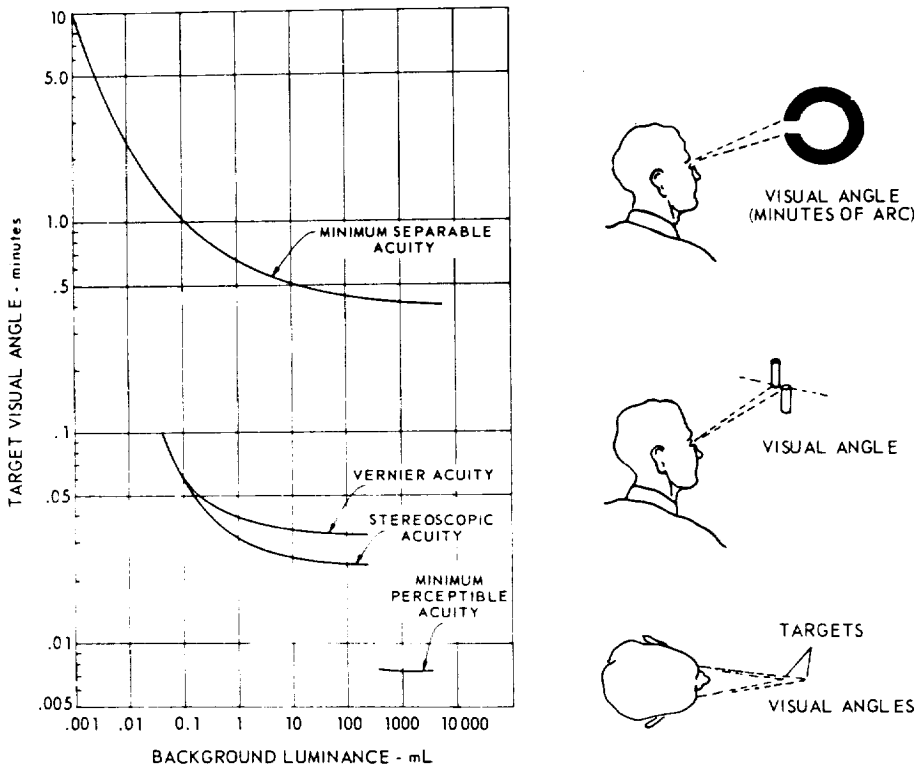
$$C_B = \frac{B_b - B_t}{B_b} \text{ and } C_B = \frac{B_t - B_b}{B_b} \text{ or } C_B \times 100 = \% \, C_B \qquad (1)$$

Contrast can vary from zero to minus one for targets darker than their backgrounds, and from zero to infinity for targets brighter than their backgrounds. Most studies of this aspect of vision consider targets brighter than their backgrounds.

Relation between target size and background luminance for targets of various contrasts is shown in Figures 2-16 and 2-17.

Thresholds in Figure 2-16 are at the 50% probability of detection. By multiplying the values by 2 (log 0.3), the values may be converted to about the 95% probability of detection. The graph shows that a reduction in any one factor — background luminance, size, or contrast — may be compensated for by an increase in one or more of the others. The relation between minimum separable acuity and background luminance of Figure 2-15 is nearly reproduced for the 100% contrast curve in this graph. The chief effect of reducing contrast is a shift of the curve upward in the direction of increased target size for 50% probability of resolving parts of a target. The family of curves also shows the discontinuity at about 0.0003 mL that marks the transition from rod to cone vision.

Figure 2-17 presents similar data for luminance contrast thresholds. Variations in luminance contrast threshold ($\Delta B/B$, where B is luminance) are shown as functions of background luminance and target size. (Pupil diameter is shown as it varies with background luminance.) Two relationships are shown very clearly by this graph: When it gets darker, objects must be a lot blacker or lighter than their background to be seen; and, at any level of luminance, small objects must have more contrast in order to be seen than large objects. In Figures 2-16 and 2-17, the subjects knew where the target would appear on the background and exposure duration varied from case to case. The times were empirically determined so that, when doubled, they did not yield a lower value of threshold contrast.



Variations in spatial acuity with background luminance for high contrast targets, considering the natural pupil and binocular vision. Minimum separable acuity defines the smallest space the eye can see between parts of a target. The relationship shown is for a black Landolt-ring on a white background. For white targets on black backgrounds, the relationship between acuity and luminance holds up to about 10 mL, above which acuity decreases because the white parts of the display blur. Vernier acuity is the minimum lateral displacement necessary for two portions of a line to be perceived as discontinuous. The thickness of the lines is of little importance. Stereoscopic acuity defines the just perceptible difference in binocular parallax of two objects or points. Parallactic angle is one of the cues used in judging depth. Beyond 2500 feet, one eye does as well as two for perceiving depth. Minimum perceptible acuity refers to the eye's ability to see small objects against a plain background. It is commonly tested with fine black wires or small spots (either darker or lighter) against illuminated backgrounds. For all practical purposes, these numbers represent the limits of visual acuity. Another type of acuity, not shown in the graph, is minimum visible acuity. This term refers to the detection by the eye of targets that affect the eye only in proportion to target intensity. There is no lower size limit for targets of this kind. For instance, the giant red star Aldebaran (magnitude 1) can be seen even though it subtends an angle of 0.0003 minutes (0.056 sec) of arc at the eye. (The conditions under which these data were obtained were nearly optimal for a given level of illumination. Changes in contrast, retinal location, rapid changes in illumination, and vibration would decrease the resolution capabilities of the eye.)

Figure 2-15

Variation in Visual Acuity with Background Luminance

(Vernier and Stereoscopic Acuity Data from Berry[36]; Minimum Perceptible Acuity Data from Hecht et al.[212]; Minimum Separable Acuity Curve after Moon and Spencer[302] Adapted by White[446])

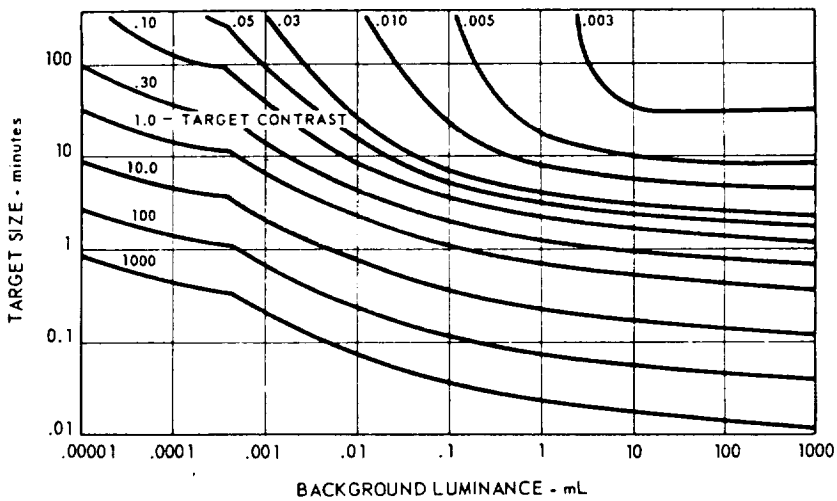


Figure 2-16

Relation Between Target Size, Threshold Background Luminance, and Contrast

(After Blackwell[47])

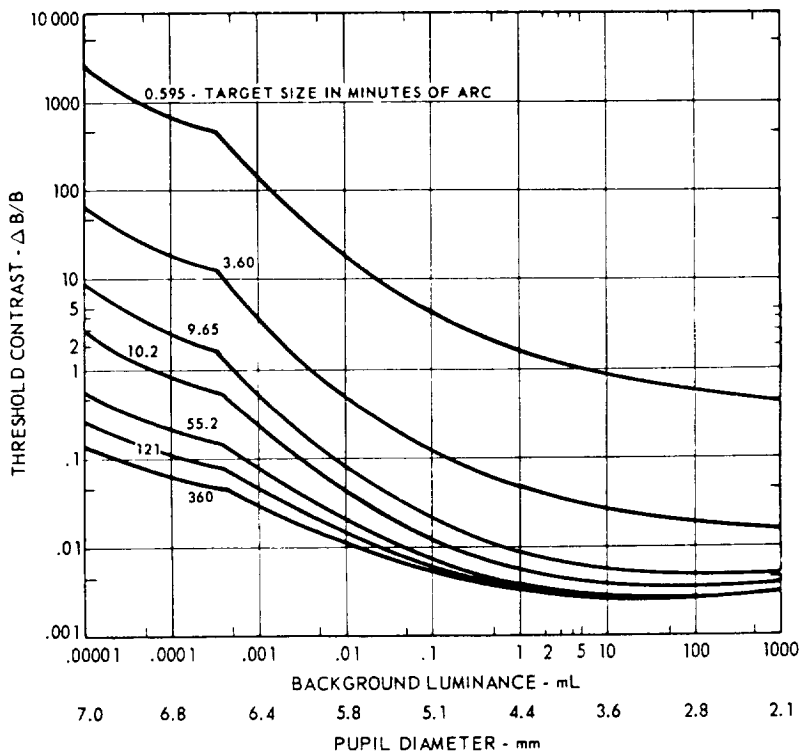


Figure 2-17

Contrast Thresholds for Different Target Sizes, Background Luminance, and Pupil Diameter at Each Level

(After Blackwell[47])

Point sources of light are defined by Ricco's law as those in which the product of threshold contrast and solid angle subtended by target are constant. Figure 2-18 represents the maximum visual angle satisfying the point source criterion at different luminance levels. Figure 2-9 presents the threshold illuminance and stellar magnitude at different background luminance levels. Figure 2-55 gives retinal image sizes for point sources at different pupillary diameters.

Increasing the size of light sources will increase their effective brightness and visibility. Figure 2-19 shows the minimum visual angle a light source can subtend at the eye and still be seen at different luminance levels of the source.

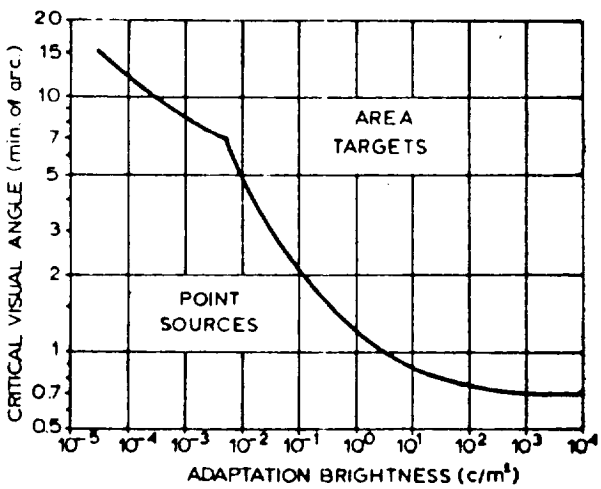


Figure 2-18

Critical Visual Angle for Point Sources Versus Area Targets.

(Adapted from Blackwell[47] by Seyb[380])

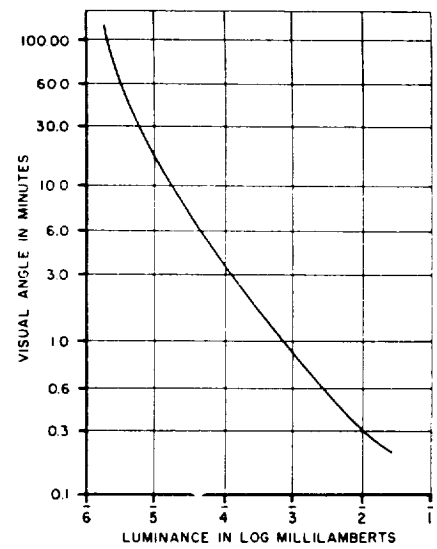


Figure 2-19

Minimum Visual Angle of a Light Source Versus Source Luminance.

(After Wulfeck[462] Adapted from Data of Lash and Prideaux[259])

For spacecraft and their markings, the target may not be circular but rectangular. When dark bars are seen on a brighter background, minimum separation between bars can be determined for specific background illumination and contrast conditions. This is shown in Figure 2-20.

There is a distinct difference between resolution of bright bar figures on a dark background and dark bars on a bright background. Figure 2-21 shows these differences as a function of retinal illuminance while observing the bars. The measure of visual acuity is the smallest distance two bars can be separated and still be seen as separate. As the illumination of the retina increases beyond about 3.2 photons (0.5 log units), the ability of the eye to discriminate between the bars begins to get worse instead of better. In other words, reflecting bars by day and luminous bars by night must be bright enough but not too bright. (For pupils of 2mm diameter, 10 photons = 1 mL.)

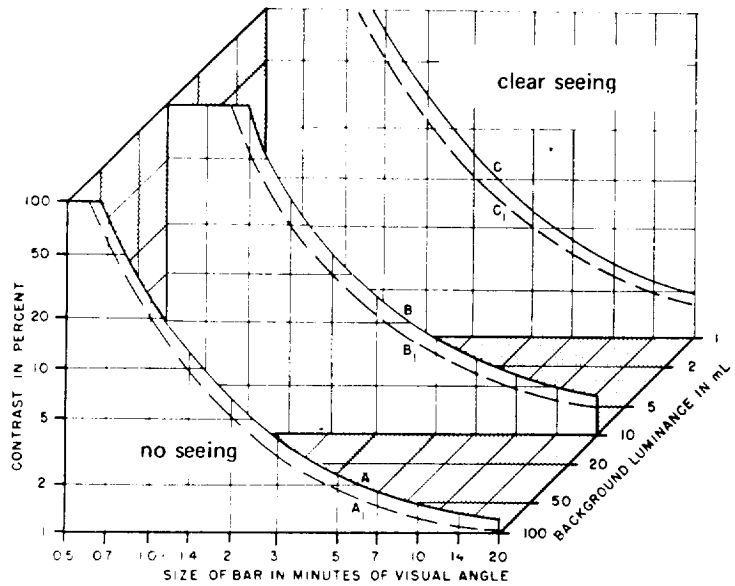


Figure 2-20

Background Luminance and Contrast Required for Bars Subtending Various Angles to be Seen Under Daylight Conditions.

(After Cobb and Moss[100])

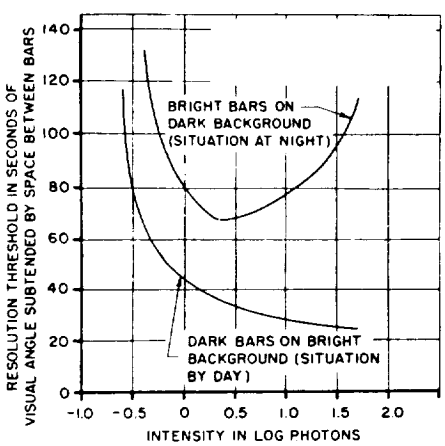


Figure 2-21

Ability to Discriminate Bright Bars Against Dark Background

(After Wilcox[451])

Figure 2-22 shows the effect of area of rectangular stimulus on threshold contrast $\Delta B/B$ for 5 ratios of length to width of rectangles. For large areas, threshold contrast for fixed area decreases as shape approaches a square. When area exceeds 100 min^2, shape again becomes unimportant. The visibility of objects in fields of high brightness is also strongly dependent on the shape factor (212). A thin wire one degree long may be seen silhouetted against a sky of high brightness of about 4000 ft Lamberts if its diameter were only 1/2 second of visual angle. Silhouetted squares must be 18 seconds long. Square objects, however, are more efficiently seen. To be seen with the same certainty, squares may be less than three times the area of line stimuli. Filters will have different relative effects on visibility of objects of different shape under the same background illuminance (212).

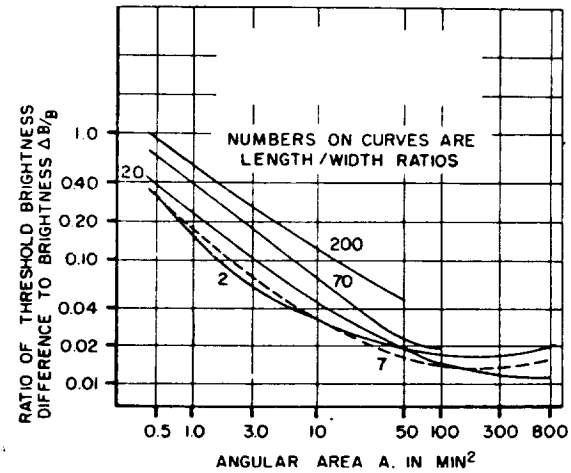


Figure 2-22

Contrast Threshold as a Function of Shape of the Stimulus

(Adapted by Wulfeck et al[462] from Lamar et al[256])

In the inspection of satellites at relatively close distances, the detection of critical detail may be important. Typical detection problems are seen in Figures 2-23a and 2-23b giving visual acuity limits for targets either brighter or darker than the background for different background luminance conditions. These curves permit prediction of visual acuity for discrimination of the shape of targets of known luminance on a background of known luminance, to luminance which the human eye is adapted (17, 371). The visual acuities correspond to the visual angles subtended by the critical detail which was needed for distinction of a square from a circle of equal area, when varying sizes.

Secondary factors often play a key role in visual tasks. Subjective sharpness of the contour border between two areas of sharply different contrast may be important in determining detail of objects under space conditions (362). Similar problems of contour sharpness are present in near vision requiring accommodation (109) and at the retinal periphery (45).

In low levels of illuminance, scotopic sensitivity shows many interesting irregularities (107, 361). Color perception is especially affected as will be discussed below.

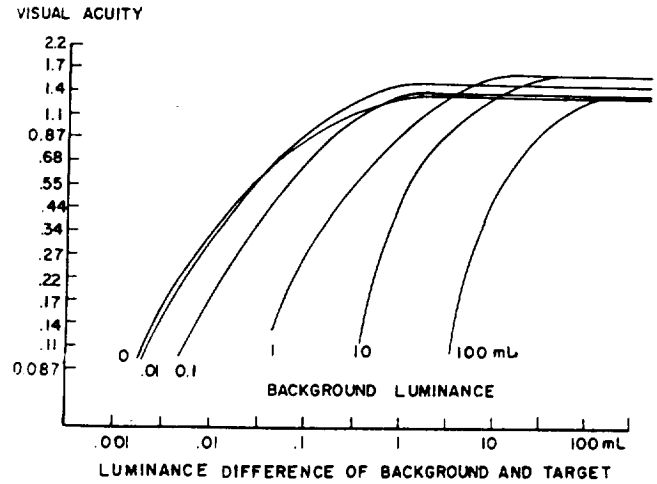
The judgment of relative brightness of several objects is a complex task which has received much study (359).

The position of target on retina as a factor in determination of visibility is seen in Figure 2-24. Figure 2-24a shows a visual acuity curve for discriminating objects at 0°, 4°, and 30° away from visual axis on retina. The advantage of foveal vision decreases with the background luminance levels. At about .001 ft L all parts of the visual field are equisensitive. Data are avail-

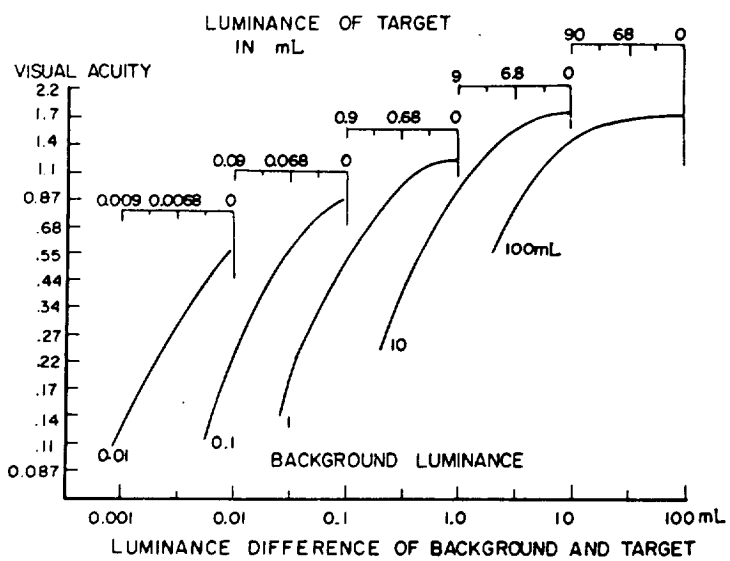
Figure 2-23

Visual Acuity for Detecting Shape of Targets

(After Schmidt[371] Adapted from Aulhorn[17])



a. Brighter than Background

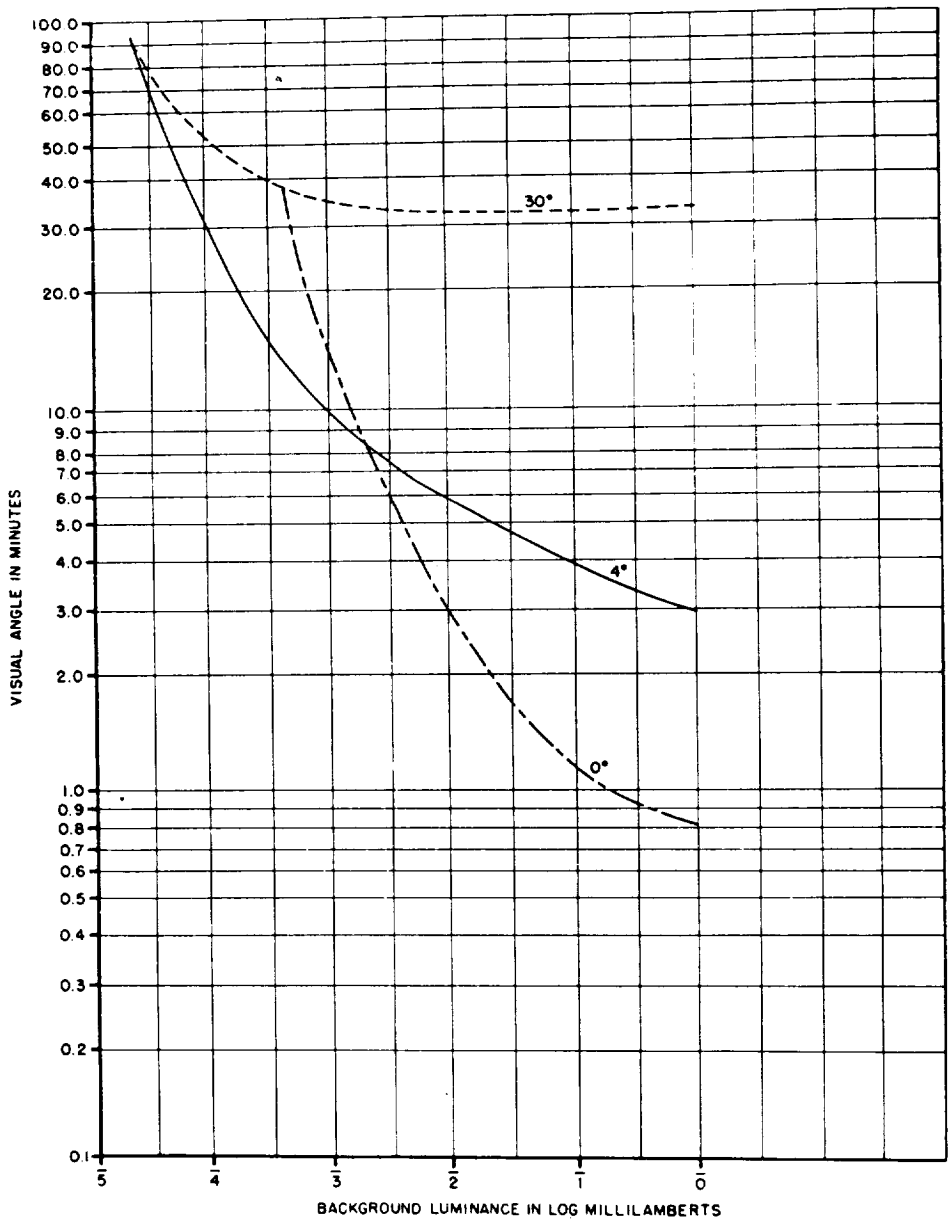


b. Darker than Background

(See text for definition of Acuity)

Figure 2-24

Position of Target on Retina as a Factor in Visibility



a. Visual Acuity Curves at Different Angles Away from the Visual Axis on the Retina as a Function of Background Illuminance.

(After Wulfeck et al[462] Adapted from Mandelbaum and Rowland[285])

able on contrast thresholds as a function of retinal position and target size during brief target exposure (407).

Figure 2-24b shows the relative photopic acuity at a fixed level of background illuminance for different angular positions from the visual axis. The blind spot is the site of the optic disc and nerve. Such values must be considered when determining objects not directly along the visual axis.

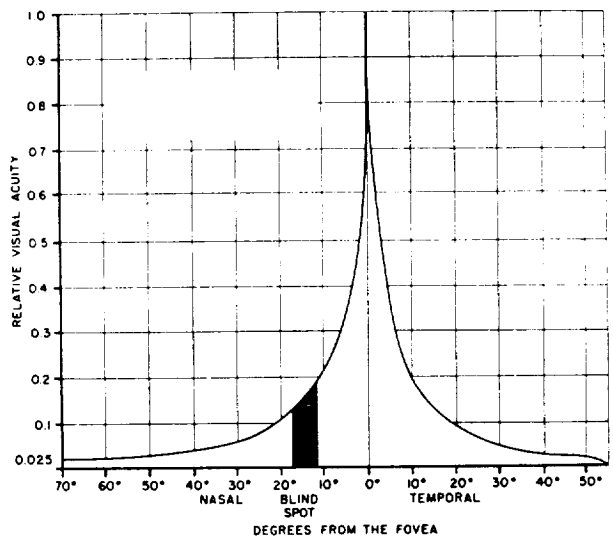


Figure 2-24b

Relative Visual Acuity at Different Angles from the Fovea for Photopic Vision.

(After Wulfeck et al[462] Adapted from Wertheim[439])

The Stiles-Crawford effect is a factor which relates to the design of optical aids (397). A given increase in pupillary area is accompanied by a smaller proportional increase in the effectiveness of the light for vision. A marginal ray is generally less effective as a stimulus for vision than a ray that reaches the same point on the retina by passing through the center of the pupil. The relative luminous efficiencies of rays entering the pupil at various points away from center are shown in Figure 2-25. Marginal rays are sometimes less than one-third as effective as are central rays. Control experiments have shown that all the rays reach the retinal surface with nearly equal intensity; hence the disproportionately low efficiency of the marginal rays is a consequence of their direction of incidence on the receptors (178).

The rods do not manifest the Stiles-Crawford effect as do the cones. Hence, it is possible to appraise the effectiveness of dim lights for the dark-adapted eye in proportion to the pupillary area prevailing at the time the observations are made. The practical consequence of the Stiles-Crawford

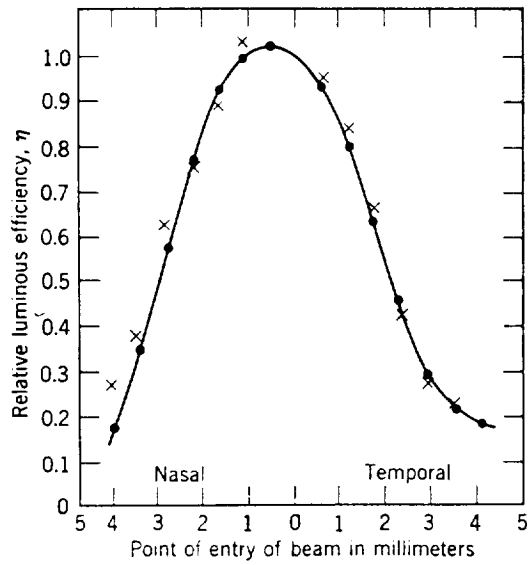


Figure 2-25

The Relative Luminous Efficiency of Light Entering the Pupil at Various Points in a Horizontal Plane Through the Center of the Eye.

Subject BHC: x left eye, • right eye.

In this figure, η is expressed as the ratio between the intensity of a central ray and that of a marginal ray, the two having been adjusted to produce equal brightness as shown by the fact that no flicker occurs with temporal alternation of stimuli.

(After Stiles and Crawford[397])

effect is that retinal illuminance per se cannot be taken as an appropriate indication of the effectiveness of visual stimulation. Thus, the troland is a unit of equivocal significance for vision at ordinary photopic levels of luminance. Nevertheless, it is a useful measure for many circumstances. Both pupil size and luminance should be clearly specified for a given situation, and under these conditions one may speak of the product in terms of trolands uncorrected for Stiles-Crawford effect. (See Table 2-2.)

Optical Aberrations of the Eye

A detailed analysis of the optical aberrations of the human eye is beyond the scope of this presentation. Data on the clinical aspects of the problem are available (1, 126, 178). The following discussion summarizes the problems from the point of view of the designer of optical equipment (178).

The surfaces of the cornea and lens are not perfectly spherical, and the optical density of the lens varies from one point to another. Furthermore, changes in accommodation produce changes in the surfaces of the lens, with corresponding changes in the aberrations of the system. (147, 226). Aberrations are greatest in the periphery of the cornea and the lens. Pupillary constriction thus improves the quality of the image formed on the retina by excluding light that passes through the peripheral portions of the cornea and the lens. Thus, problems of spherical aberration are greatest when the pupil is larger or the fired luminance is low.

The effects of "night myopia" have been attributed by some mainly to spherical aberration,(251) although others have attributed this phenomenon mainly to accommodative effects (330).

For all small pupil diameters (i.e., less than 2.5 mm, or perhaps 4 mm in individual cases) the effects of spherical aberration may be negligible by comparison with those of diffraction (80, 178).

One may conclude that spherical aberration probably does not have an important influence on measurements of visual acuity at moderate to high intensity levels for the normal eye. It may, however, be a significant factor in night vision, where pupillary apertures are large enough to bring in significant blurring by aberration effects on the marginal rays.

Chromatic aberration is another problem, especially in the viewing of angularly small objects (117, 147, 178, 203, 204, 225, 433). Here the seriousness of the effect on acuity is largely a function of the wavelength distribution of the light used for viewing the test object.

For all low to moderate levels of intensity, acuity is better when sodium or mercury vapor lamps were employed rather than tungsten incandescent lamps (373). At the levels of intensity above 4000 meter-candles, however, the various illuminants were all found to yield similar acuity scores. Monochromatic blue light yields poor acuity values, and light from the red end of the spectrum, while not so bad as blue, is definitely inferior to green or yellow for best acuity. These matters are further complicated by the influence of accommodation, which appears to be most strongly activated by yellow light and less so by lights of other hues (434). The macular pigment absorbs a relatively large proportion of the blue light that would otherwise affect the retina. This has been interpreted to mean that the macular pigment serves as a filter that, among other things, acts to reduce the chromatic aberration of the eye for any white light that contains considerable amounts of blue light.

Errors of diffraction are usually more significant than errors of chromatic or spherical aberration (117, 126, 178). The fairly constant level of visual activity in the range of pupil diameters from 2.5 to 5 mm probably represents a balance between the reduction in diffraction and the increase in optical aberrations. The testing and correction of refractive error of the eye is well covered by many textbooks of opthalmology (117, 126). Enhancement of night vision depends heavily on correction of aberrations resulting from dilated pupils (343).

Search and Visibility

Much study has gone into visual search techniques and strategy with variable target and ambient conditions (43, 46, 50, 53, 77, 92, 167, 168, 169, 170, 171, 172, 173, 174, 201). Recent reviews are available on visual detection of targets in search (132, 141, 151, 305, 407).

Optimization of search strategy involves the concept of the visual detection lobe (132, 209). Recent work has covered eye movements in search (108, 143, 377, 453, 454, 456, 463), critical visual variables in the early period of search (428, 429), and search time as a function of visual acuity of the observer (140, 235). The dwell time in typical detection task is the time the eyes remain stationary between fixations and approaches a value of

1/3 of a second (441). For discrimination tasks, the value may increase up to one second or more (159). The stimulus duration is therefore a key variable in search strategy and visibility predictions (see Figures 2-33 and 2-34).

If one does not eliminate the assumed integrating effects of the 30 to 50 per second components of the normal oscillatory movements, it has been shown that contrast threshold values depend primarily on the target size and position. The probability of detecting a target of particular size and location is ultimately determined by the number and kind of retinal elements and their momentary threshold; receptor interconnections; the frequency and angular extent of eye movements; and the duration of target (407). Visual response in the field condition must therefore be converted from basic laboratory data often representing optimum conditions. Probability functions can be determined from contrast thresholds at P = 0.5 for other probabilities (52). Many of the field variables can be roughly quantitated.

Figure 2-26 gives multiplication factors to be used in roughly correcting for visual accuracy and speed during non-standard visual tasks. Figure 2-26a suggests the amount that illumination must be increased to obtain increased accuracy of vision. These data on visual task performance as a function of other factors (speed, acceleration, etc.) have been based on 50% reading accuracy. The multiplying factor was determined by evaluating data on reading instruments and on identifying the area occupied by a target (382). Since the shape of the curve is influenced by contrast, adaptation of the eye, acuity, speed of vision, and task difficulty, this curve must be used only as a rough estimate of error reduction.

Figure 2-26b suggests the amount that illumination must be increased to obtain increased speed of vision. The speed of vision is expressed in discriminations per second with discrimination task being the identification of the opening in a Landolt ring (capital letter C). The determination of the number of discriminations per second involved in a given task would be based on a correlation between the time to do this task and the time to identify C openings with all conditions being identical.

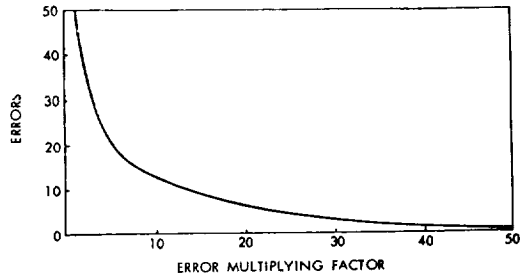
Figure 2-26c suggests multiplication factors for contrast thresholds (Figures 2-16, 2-17, 2-20, 2-23) when inadequate knowledge is available regarding various target properties (48, 49, 52, 132). They have been obtained from relatively few experiments and should be used with caution.

Vigilance is a key factor in search for targets which occur infrequently. Data on the visual aspects of vigilance are available (137, 233). Several models of vigilance have been proposed recently (72, 81, 233, 282, 374, 403) and current studies are being directed to fitting visual search problems to these models (232, 270, 299). Visual alertness may be estimated from electroencephalographic data (34). The effect of simultaneous auditory noise and other extraneous stimuli on vigilance is also under study (71, 188, 202, 437, 467).

For general use, a contrast correction factor of 1.19 for vigilance alone has been recommended (30). This factor is probably satisfactory when the

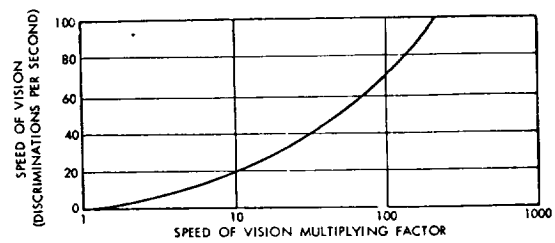
Figure 2-26

Correction Factors for Visual Accuracy and Speed in Search Operations



a. Illumination Increase Required to Reduce Error in Vision

(After Shearer and Downey[382])



b. Illumination Increase Required to Heighten Speed of Vision

(After Shearer and Downey[382])

Target Properties				Correction Factor (↓)
Location ±4° or more	Time of occurrence	Size (3 used)	Duration (3 used)	
+	+	+	+	1.00
+	-	+	+	1.40
+	-	+	-	1.60
+	-	-	+	1.50
+	-	-	-	1.45
-	+	+	+	1.31

+, knowledge; -, lack of knowledge

c. Contrast Correction Factors to be Applied When Observer Is Deprived of Knowledge of Various Target Properties.

(Adapted from Blackwell[48, 49] by Duntley[132])

stimuli occur randomly and with an average frequency of 1 or 2 in 20 min, higher occurence rates requiring less correction.

Trained observers perform better than inexperienced ones, and the magnitude and time course of practice effects are greater for more complex visibility tasks. A recent study indicates the character of the practice effects found in a simple laboratory detection experiment, and shows that a correction factor of 1.90 in contrast will compensate for the difference between trained and naive observers (311). This value is in excellent agreement with the factor reported of 2.00 for a different data collection method (32). All of these contrast multiplication factors are sequentially applied in determining the contrast needed for a given probability of detection.

Final target aquisition times are very sensitive to specific visual functions in question (356). In a complex task each factor must be considered individually and in interaction before adequate predictions can be made. Many of the more clear-cut personal and environmental influences will be discussed below.

Determination of visual range for a high probability of detection within the Earth's atmosphere is a complex calculation (132, 252, 293). Figures

2-27a and 2-27b represent graphs permitting range estimates in daylight and starlight within the Earth's atmosphere. Similar graphs are available for other lighting conditions (133). Sighting ranges have also been calculated for night and twilight light operations under field conditions (380). For stationary targets, the sighting range is practically the same as maximum detection range; for moving and approaching targets, the sighting range can be considered the upper limit of the maximum detection range. Visual detection lobe theory has been recently applied to air to ground observations and range calculations (209).

The strategy and optimization of search for objects at sea has received extensive review (252). Data are also available for visibility under the sea (134, 245, 246), under white-out conditions (243), and in jungle terrain (123).

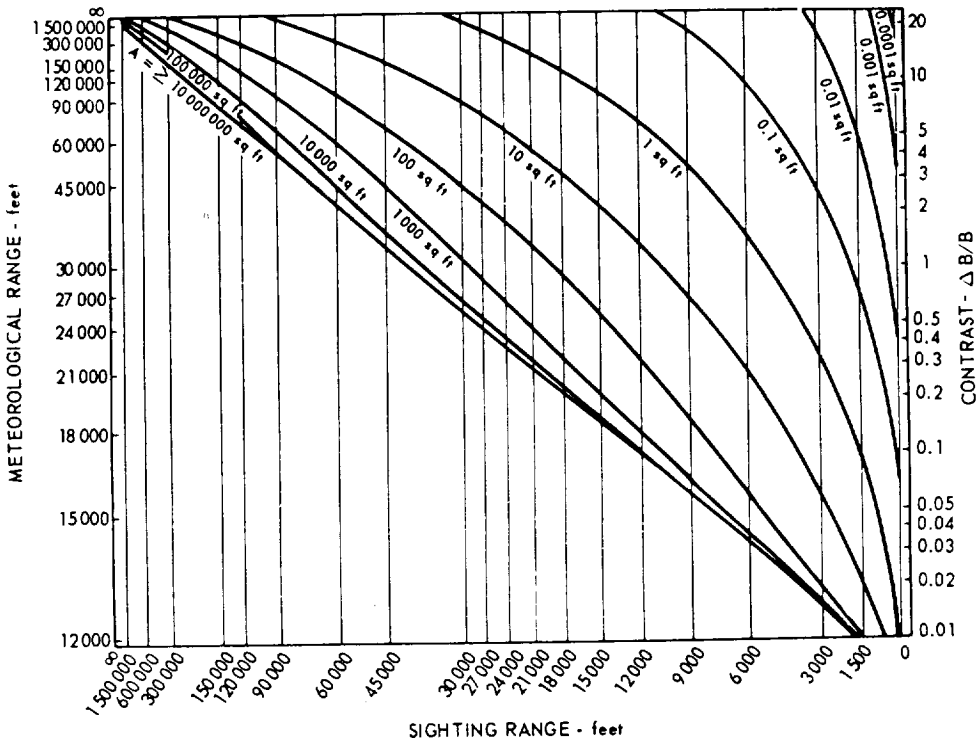
Color

Color is an important factor in the design of cockpit displays and in optimization of visual detection and identification (25). Figure 2-28 shows the eye is twice as sensitive to a yellow-green of 550 mμ, as it is to a blue of 450 mμ, and many times more sensitive to a yellow-green than to violet and red, at the ends of the visible spectrum. The situation is further complicated by differences in the responses of individuals (177). Spectral sensitivity curves are a function of the level of illumination, in that the relative function of rods and cones are dependent on this factor.

Visual Acuity as a Function of the Color of Illuminant

The color of the illuminant can be controlled either at the light source or by filters between the source and the observer's eyes. Both methods give the same effect. Colored illuminants cause the loss or reduction of color contrast and the distortion of the normal luminance relations. Objects of the same color as the illuminant will be relatively increased in luminance and may become invisible against a light background. Objects of complementary color will be darkened and may be invisible against a dark background. This effect can be used to advantage in some highly specific applications. In most cases this distortion of normal brightness and color relationships is a serious handicap, and greatly reduces the total information which can be resolved by the eye.

Experimental findings concerning visual acuity and color of the illuminant have been somewhat contradictory (26, 146). When there is a large luminance contrast between test object and background, visual acuity varies only slightly with wavelength and is generally best near the middle of the visible spectrum, if all test objects are of equal luminance. Reducing the luminance contrast between test object and background degrades acuity similarly at all wavelengths so there is little, if any, interaction between wavelength and contrast (89). Visual acuity with red and blue backgrounds of different luminance is shown in Figure 2-29. (See also chromatic aberration.)



This graph shows the sighting range (distance in feet) of targets viewed against the sky, background luminance 1000 mL (full daylight) at probability of detection of 95%. Meteorological range is the distance at which apparent brightness contrast is reduced by atmospheric scatter to 2% of inherent contrast between the object and sky. Contrast is the ratio of the luminance difference between target and background and the luminance of the background ($\Delta B/B$).

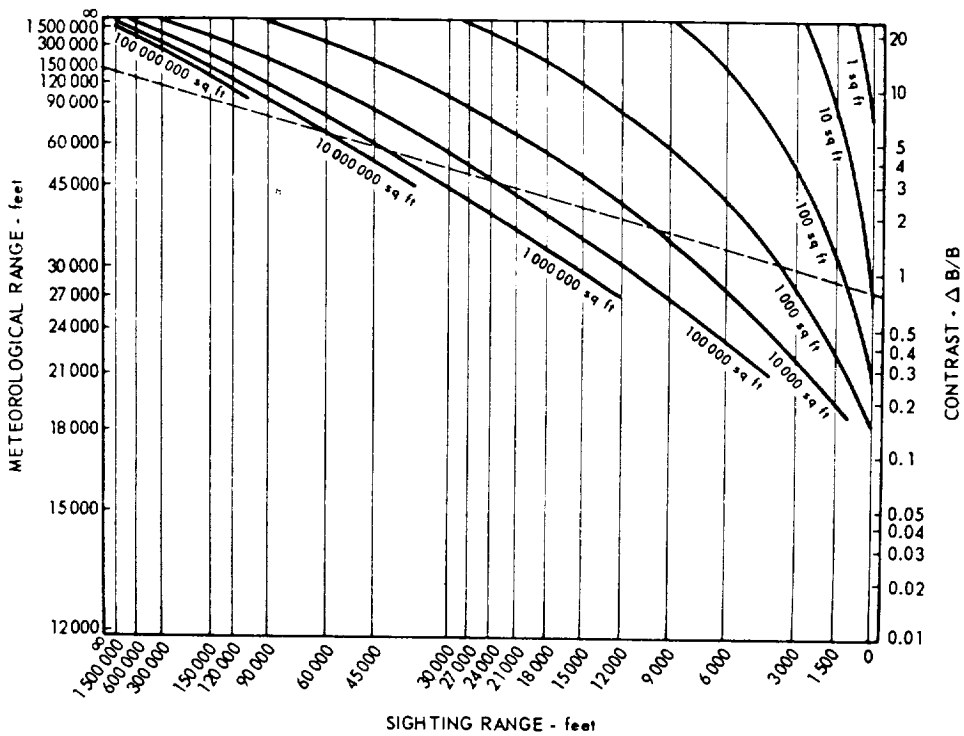
A straight line connecting meteorological range and contrast will intersect a family of curves for various target sizes, which are shown as areas (A) in square feet. The visual range is obtained by projecting up or down to the range scale. By selecting meteorological range at its infinity point, the graph may be used to find threefold contrast for any object of a given size at any assigned distance.

The graph does not apply to long narrow targets, but does apply to targets that are not very out-of-round.

Figure 2-27a

Visual Range in Natural Light - Daylight

(After Middleton[293] Adapted from Duntley[133])



This graph shows the sighting range of circular targets against the sky with a background luminance 0.0001 mL (starlight). The following is an example of the use of the nomogram: Find the range that an object 100 sq ft in area could be seen in starlight when the meteorological range is 150,000 feet and the contrast of the object and sky is 0.8. A straight line across meets the given range and contrast. The range is read off where the line intersects the 100 sq ft curve. Under these conditions a 100 sq ft target will be sighted with a probability of 95% at 1200 feet.

Figure 2-27b

Visual Range in Natural Light - Starlight

(After Middleton[293] Adapted from Duntley[133])

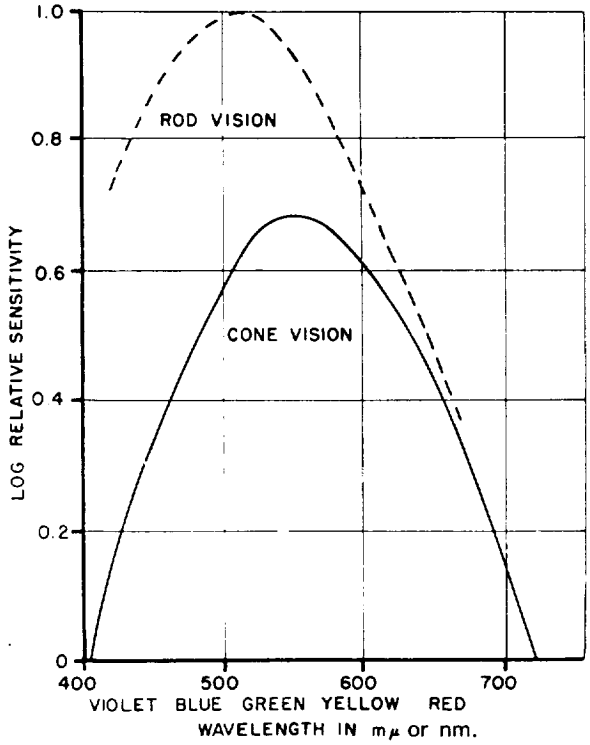


Figure 2-28

Standard Luminosity Curves: Relative Sensitivity to Radiant Flux as a Function of Wavelength

(After Hecht and Williams[213])

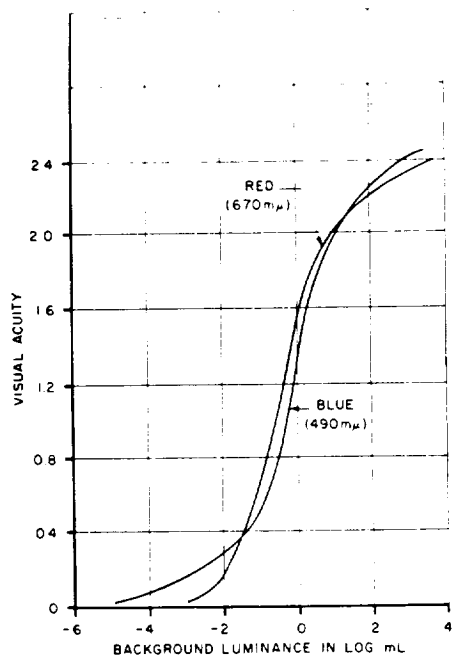


Figure 2-29

Visual Acuity as a Function of Color of Illumination

(After Chapanis[93] Adapted from Schlaer et al[384])

The extent to which acuity can be improved depends upon the particular colors used. The highest color contrast possible produces visual acuity which is equivalent to the acuity produced by a brightness contrast of 35% (135). However, acuity is increased much more by increasing brightness contrast than by increasing color contrast.

There is a frequent need to see and to identify objects on the basis of the color of the objects' surfaces. One major consideration is the ability with which the object may be seen against its background. Since detectability is increased when color and brightness contrast between the object and the background are increased, such objects as life rafts, parachutes, survival tents, path markers, and other such objects should have carefully chosen colors and brightness. Generally speaking, orange (International Orange) is seen best at great distances. Detectability can be further increased by addition of fluorescence which increases brightness and contrast. The unnaturalness of these colors also results in heightened conspicuity (406). Fluorescent orange, neon red, and red are recommended for survival equipment that must be seen at great distances. However, if the background is predominantly orange, red, or brown, objects should be green for maximum detectability. Against blue-green foliage or water, orange, red, or neon red of high brightness are best.

Color Recognition Thresholds

Signal lights used in air and marine navigation are viewed at great distances. The visual angles subtended by such sources are small and can be considered as points sources of light. The recognition of a signal light color depends upon (1) the intensity of the light source, (2) the brightness of the background, and (3) the particular colors observed. Figure 2-30 shows the illumination at the eye of a point source signal light that will be correctly identified 90% of the time for various colors viewed against various neutral background brightnesses. It indicates that yellow signal lights require the greatest intensity. This study also revealed that red and green signal lights were rarely interchanged, that is, red was rarely called green and green was rarely called red. On the other hand the yellow light was frequently confused with red. The confusion of color determination at threshold has been recently reviewed (149, 357, 435).

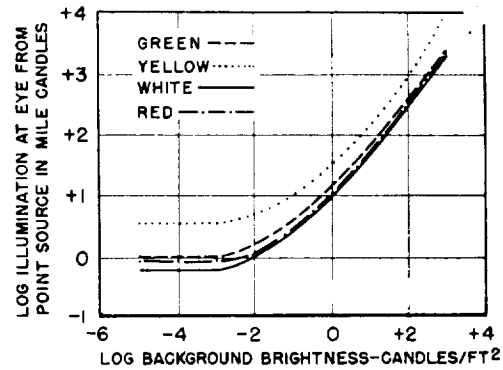


Figure 2-30

Color Recognition of Point Sources of Light

(After Baker and Grether [25] Adapted from Hill[217])

These data apply to situations where the observer knows the location of the signal. In actual situations the observer usually knows only the general direction of a signal light. For such situations the threshold recognition values should be doubled (48, 164, 177). The signals can be seen at lower intensities than shown on the graph, but the colors may not be identified correctly. Intermittency of color flashes is also a factor to be considered (435).

Color Specification

Color may be considered as having three psychological components: hue, saturation, and brightness. Most systems of color specification make use of these three concepts in one form or another.

Hue is the aspect of color commonly denoted by such names as red, yellow, green, blue, orange, and many others. The most closely related physical property of light is wavelength -- though the hue purple does not correspond to any wavelength in the spectrum.

Saturation is defined as the degree to which a sensation of hue differs from a gray of the same brightness. Colors that are 100 percent saturated are called spectrum colors. When white light is added to a spectrum color, the spectrum color decreases in saturation. For example, a spectrum red becomes more or less pink when it is mixed with white light; it is still red in hue, but its saturation has decreased.

The sensation of brightness is related to the amount of luminous flux reaching the eye from an object or light source. Other things being equal,

a source of high intensity or luminance will seem bright-colored -- bright red, bright blue, etc., -- while a source of low intensity or luminance will seem dark - or dull-colored. A sample of red that seems dark on a cloudy day will seem bright on a sunny day; the hue and saturation remain the same, but more luminous flux is reaching the eye.

Systems of color specification must relate colors to a standard light source (39, 65). The most objective method in color specification is the tristimulus colorimetric method (177). The International Commission on Illumination (ICI) chromaticity diagram is an example of this approach. Color may also be specified by visually matching samples with printed, dyed, or painted standards. The Munsell Atlas contains painted samples of all the colors in the system, presented in a three-dimensional array with hue, saturation, and brightness recorded on the axes (309, 310). Color may be used in coding, that is, specifying the correct identification of an object by its color. For example, wires, resistors, pipe lines, gas cylinders, and many other objects are color coded. Since errors in reading the color code may be disastrous, it is important to understand the sensitivity of color discrimination.

Hue discrimination is usually measured in terms of the smallest difference in wavelength that two test fields can have and still be interpreted as of different hues. Figure 2-31 shows variations in hue discrimination through the visible spectrum. Changes in hue discrimination are not equal for equal increments of wavelength (λ). At high luminance (10 mL or better) and saturated colors, 128 hues can be distinguished. The difference threshold in the blue-green and yellow portions of the spectrum is of the order of one millimicron (mμ). At the red level of the spectrum, the difference must be as great as 20 mμ before it is detected. Data are also available on brightness saturation discrimination but these are not primary factors in coding (462).

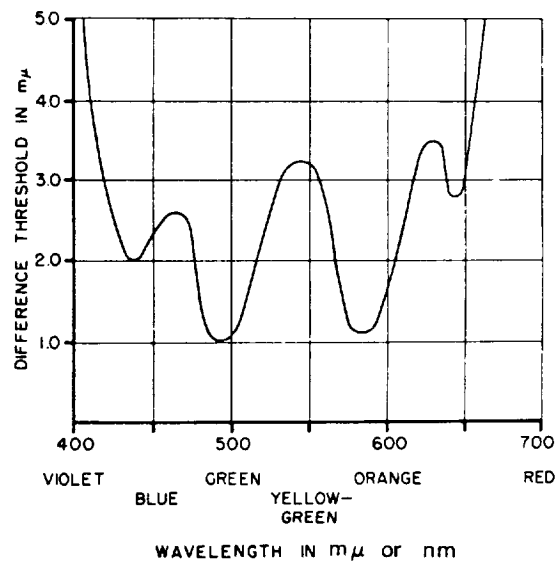


Figure 2-31

Hue Discrimination

(After Wulfeck et al [462])

A large proportion (6%) of the healthy male population possesses a significantly reduced ability to distinguish color differences. Only .003% of the population are completely color blind, that is, they see only various shades of gray. Since color coding is frequently used with unselected populations, at least with respect to color vision, the selection of the particular colors for coding becomes an important consideration. The four colors listed in Table 2-32a are considered ideal for coding because color deficient individuals can also easily recognize them (25). The numbers refer to the Federal Specification TT-C-595, 'Colors for Ready Mixed Paints,' with the exception of blue (10B 7/6) which is a Munsell notation (309, 310). However, more than four colors will frequently be required

Table 2-32

Color Code Recommendations for Pigments and Indicator Lights

(After Baker and Grether[25] and NASA CSD-A-096[423])

a. Ideal For Color-Blind Persons

Black	1770
White	1755
Yellow	1310
Blue	10B 7/6

b. For Use When More Colors Are Needed

Red	1110	Blue	10B 7/6	White	1755
Orange	1210	Purple	2715	Black	1770
Yellow	1310	Gray	1625	Buff	1745

c. Coding of Simple Indicator Lights

LIGHT	RED	AMBER	GREEN	WHITE
1/2 inch diameter steady	Malfunction, action stopped, failure, stop action	Delay, check, recheck	Go ahead, in tolerance, acceptable, ready	Functional or physical position, action in progress
1 inch diameter steady	Master summation, (system or subsystem)	Extreme caution (Impending danger)	Master summation, (system or subsystem)	N/A
1 inch diameter flashing (3-5/sec.)	Killer warning (personnel or equipment)	N/A	N/A	N/A

to code objects. The nine colors listed in Table 2-32b were selected to be the least confusing for individuals with normal and color-defective vision (14).

Color-coded signal lights are used on display panels, maintenance equipment, and in navigational aids to air, marine, and surface vehicles (65). Only three colors are recommended for signals if color defective observers are expected to respond correctly to these signals. These three colors are aviation red, aviation green, and aviation blue as defined by the Army-Navy Aeronautical Specification AN-C-56, 'Colors, Aeronautical Lights and Lighting Equipment.' Aviation blue is distinguished from red and green only at moderate distances. It must be noted that the specific requirements for these colors must be adhered to if the code is to be used by color deficient personnel because there are many reds, greens, and blues that will be confused. Also, no attempt should be made to include white or yellow in conjunction with the three recommended colors because the color-deficient individuals may confuse red with yellow and green with white.

A color-coding scheme for indicator lights on instrument panels conforming to the identification colors listed in MIL-C-25050 as suggested for the Apollo system are noted in Figure 2-32c (3).

Red - Red is used to alert an operator that the system or any portion of the system is inoperative and that a successful mission is not possible until appropriate corrective or override action is taken. Examples of lights which are coded red are those which display such information as: no-go, error, failure, malfunction, etc.

Amber - Amber is used to advise an operator that a condition exists which is marginal insofar as system effectiveness is concerned, that an unsatisfactory or hazardous condition is being approached or exists but that the system can still operate (battery approaching replacement time, etc.).

Green - Green is used to indicate that a unit or component is in tolerance or a condition is satisfactory and that it is all right to proceed (go ahead, in tolerance, ready, acceptance, normal, etc.).

White - White is used to indicate those system conditions that are not intended to provide a right or wrong implication, such as indications of alternative functions or are indicative of transitory conditions, where such indication does not imply success of operations.

Blue - Blue is used as an advisory type light, but preferential use of blue is discouraged.

The flash rate for flashing warning lights should vary from 3 to 5 flashes per second with on time being approximately equal to off time. The indicator should be designed so that if energized and the flasher device fails, the light will come on and burn steadily. If simple-type indicator lights (rather than legend type lights) are used for emergency conditions (personnel or equipment disaster), such functions are indicated by a 1-inch diameter red flashing light and cautionary conditions (impending danger) by a 1-inch diameter steady amber light. Master summation indications; system or subsystem, is

indicated by 1-inch diameter steady red or green lights. Indication of all other conditions is by 1/2 inch diameter steady lights. One-inch diameter lights are discriminately brighter than 1/2-inch diameter lights. With the exception of small flashing white call lights commonly used on communication panels, no other flashing lights are used. Auditory signals may be used to complement the visual display (31).

Several general reviews of factors in color coding are available (106, 240). Color mixture functions at low luminance levels have also received recent study as have distortions of color during underwater observation (246, 447). Data are also available on the visibility of colored smoke signals from the air (438). The effect of color on the internal illumination and habitability of spacecraft is discussed in another section.

Duration of Visual Exposure and Intermittent Illumination

When a target appears as a short flash up to about 0.1 sec. duration (this limit depending on the conditions), the effectiveness of the light increases linearly with exposure time as expressed in Bloch's law. On longer exposures, up to a few tenths of a second or longer, the time factor is less effective as expressed in Blondel and Rey's law (54). Finally, above a critical time the effect of a light becomes independent of the duration. These laws, which express the temporal summating ability of the visual system, may also be valid for a moving object as long as its image stimulates the same receptive fields of the retinal elements. Figures 2-33 and 2-34 are demonstrations of the effect of target size and target exposure on the contrast thresholds for stationary targets. At any luminance level, less time is required to see bigger objects. When size is held constant, less time is required to see at higher luminance levels.

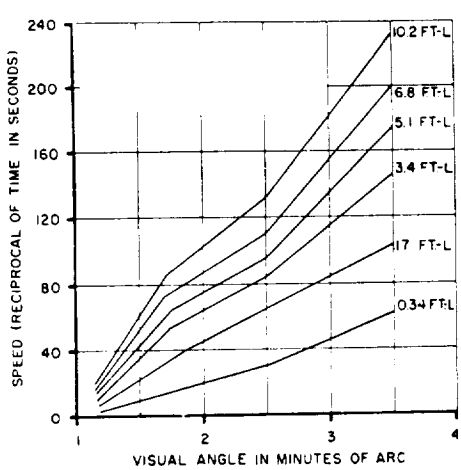


Figure 2-33

Visual Acuity as a Function of Time of Exposure to Viewed Object

(After Chapanis[93] Data of Ferree and Rand[145])

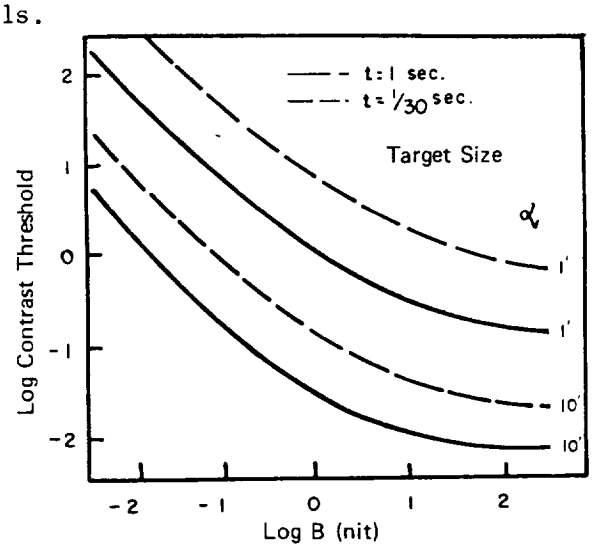


Figure 2-34

Contrast Thresholds in Dependence of Target Size and Time of Exposure

(After Schmidt[371] from Data of Blackwell et al[50])

Intermittent signal and warning lights are often more detectable than steady lights. This factor may be of value in space operations. Although a target may be bright enough to be visible, the pilot may not detect it against the star background -- particularly if its motion is very slow. Because the apparent motions at the initiation of rendezvous are, in general, very slow, this is an extremely important problem in acquisition. If the light is interrupted so as to flash off and on, it would be much more readily detected than a steady light (54, 312). The problem then concerns the optimum flash rate and flash duration. The effect of flash duration on the apparent intensity of a light seen by the human eye is shown in Figure 2-35. In this figure, a steady light which is just barely discernible is used as a datum reference with a relative intensity level of unity. The figure shows that little increase in relative intensity is required down to flash durations approaching 0.2 second. For flash durations less than one-tenth second, however, the required relative intensity increases as an inverse function of time. For example, if the flash duration is about 0.003 seconds, the intensity relative to the steady light must be increased by a factor of about 100. The curve of Figure 2-35 can be approximated by the equation:

$$E = E_O \left(\frac{t + a}{t}\right) \qquad (2)$$

where

E = intensity of flashing source required to appear as bright as E_O

E_O = intensity of steady source

t = duration of flash, sec.

a = curve fitting constant equal to 0.21 second

This expression is known as Talbot's law.

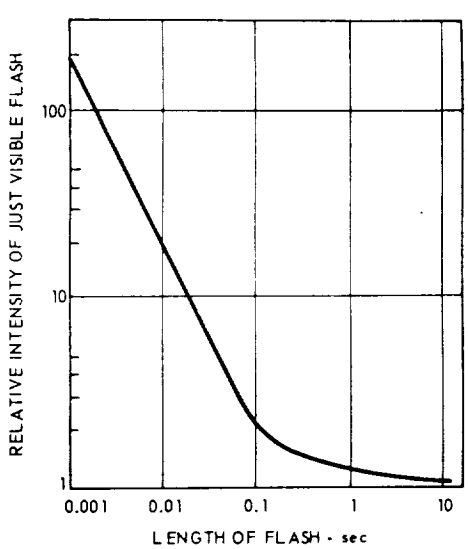


Figure 2-35

Visibility of Flashing Sources of Light

This Figure shows how intense a flash of light must be in order to be seen at the 50% probability level. Note that very short flashes must be much more intense than long flashes if they are to be seen. The detection of colored lights requires about the same illumination at the eye as detection of white light.

(Adapted from Blondel and Rey[54])

There are many variables altering the perception of intermittent light signals (157, 158, 247, 275, 435). Repeated flashes of light frequently lead to contradictory responses at the same wavelength. The variability in color recognition near the threshold is well known (149, 435). An observer who is expecting a brief and small, circular, colored light signal in the darkness and required to identify the color of the signal may be especially confused (435). When the signal is perceived as a circle, there is a good probability of correctly identifying its color. When it is perceived as a mere light sensation, quite shapeless, the signal may appear as achromatic regardless of actual color. When the signal appears distorted in shape between the two extreme situations described above, little confidence may be given that the assumed color response is correct. The perception of circular shape requires a less intense stimulus for red stimuli than for other colors.

The perceived brightness of intermittent light is greater below fusion than at higher frequencies (brightness enhancement) (28, 421). The maximum enhancement above the Talbot plateau level appears to be at about 4-5 cps (103).

Visual noise interferes with perception of intermittent stimuli and may cause false alarms in operational situations (358, 360). In search situations, the effect of flash distribution and illumination level of low intensity stimuli may be important (450).

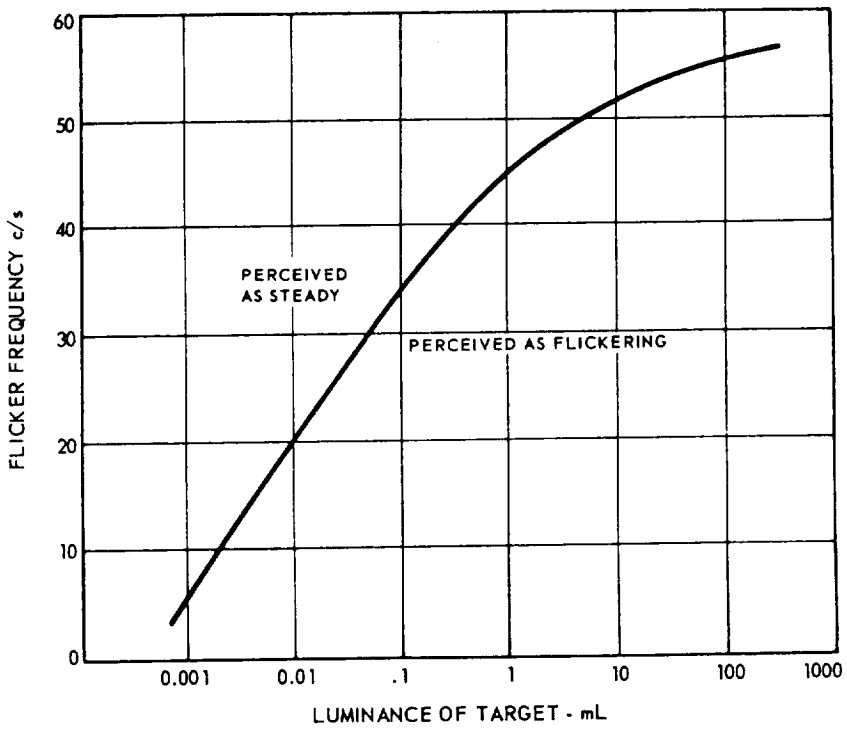
It has been noted that the threshold for visibility at night is about 0.13 km-c (.05 mi-c) but in operational conditions for semi-trained subjects who have large and ill-defined solid angles to search, 0.94 km-c (.36 mi-c) would be a more reasonable threshold for detectability. In scotopic and mesopic vision, the rod perception of contrast may be improved by intermittent illumination of peak luminance level equal to an equivalent steady illumination. There are ideal wave forms and frequencies for each color (44).

In the case where the subject knows the position in space where a flash is to occur, the simple reaction time is a decreasing, negatively accelerated function of flash luminance (261). Flash duration has no clear effect on reaction time.

The flickering effect of intermittent light at around 8 pulses per second may be disturbing to some people (6). A small percent of the population may even develop epileptic seizures from the flicker (35, 290, 418). At high frequency of flicker, fusion of the image occurs and the light is perceived as steady. Figure 2-36 represents this phenomenon as a function of luminance. The data are valid only for white light on the fovea. The flicker fusion frequency is dependent on the functional state of the central nervous system.

Visual Fields

The limit of field of vision possible with eyes and head fixed or free to move about is seen in Table 2-37. The monocular and binocular fields for achromatic targets with eyes fixed are seen in Figure 2-38a and c. Chromatic targets alter the field of vision as seen in Figure 2-38b. Helmets and



The graph shows the relation between critical fusion frequency (CFF) and luminance. The curve defines the boundary between those combinations of target luminance and flicker frequency that are perceived as flickering and those perceived as steady. CFF is the lowest frequency (c/s) of flashing that can be perceived as steady. Luminance is the variable with the greatest influence on CFF. Other variables are target size, color, lengths of the light-dark cycle, brightness of the surround, region of the retina stimulated, and individual differences. The data shown in the graph are based on a two-degree, achromatic stimulus at zero degrees of angular eccentricity.

Figure 2-36

Temporal Discrimination of White Light at the Fovea

(Adapted from Hecht and Verrijp[211] by White[446])

Table 2-37

Binocular Visual Fields with Head and Eye Movement

(After Wulfeck et al[462] from data of Hall and Greenbaum[195])

MOVEMENT PERMITTED	TYPE OF FIELD AND FACTORS LIMITING FIELD	HORIZONTAL LIMITS		VERTICAL LIMITS	
		Temporal Ambinocular Field (each side)	Nasal Binocular Field (each side)	Field Angle Up	Field Angle Down
Moderate movements of head and eyes, assumed as:	Range of fixation	60°		45°	
Eyes: 15° right or left 15° up or down	Eye deviation (assumed)	15°	15°	15°	15°
	Peripheral field from point of fixation	95°	(45°)	46°	67°
Head: 45° right or left 30° up or down	Net peripheral field from central fixation	110°	60°***	61°	82°
	Head rotation (assumed)	45°	45°	30°*	30°*
	Total peripheral field (from central body line)	155°	105°	91°	112°**
Head fixed Eyes fixed (central position with respect to head)	Field of peripheral vision (central fixation)	95°	60°	46°	67°
Head-fixed Eyes maximum deviation	Limits of eye deviation (= range of fixation)	74°	55°	48°	66°
	Peripheral field (from point of fixation)	91°	Approx (5°)	18°	16°
	Total peripheral field (from central head line)	165°	60°***	66°	82°
Head maximum movement Eyes fixed (central with respect to head)	Limits of head motion (= range of fixation)	72°	72°	80°*	90°*
	Peripheral field (from point of fixation)	95°	60°	46°	67°
	Total peripheral field (from central body line)	167°	132°	126°	157°**
Maximum movement of head and eyes	Limits of head motion	72°	72°	80°*	90°*
	Maximum eye deviation	74°	55°	48°	66°
	Range of fixation (from central body line)	146°	127°	128°	156°**
	Peripheral field (from point of fixation)	91°	Approx (5°)	18°	16°
	Total peripheral field (from central body line)	237°	132°	146°	172°**

*Estimated by the authors on the basis of a single subject.

**Ignoring obstruction of body (and knees if seated). This obstruction would probably impose a maximum field of 90° (or less, seated) directly downward; however, this would not apply downward to either side.

***This is the maximum possible peripheral field; rotating the eye in the nasal direction will not extend it, because it is limited by the nose and other facial structures rather than by the optical limits of the eye. The figures in parentheses on the line above are calculated values, chosen to give the maximum limit thus indicated.

Notes: The ambinocular field is defined here as the total area that can be seen by either eye; it is not limited to the binocular field, which can be seen by both eyes at once. That is, at the sides, it includes monocular regions visible to the right eye but not to the left, and vice versa.

The term binocular is here restricted to the central region that can be seen by both eyes simultaneously (stereoscopic vision). It is bounded by the nasal field-limits of the eyes.

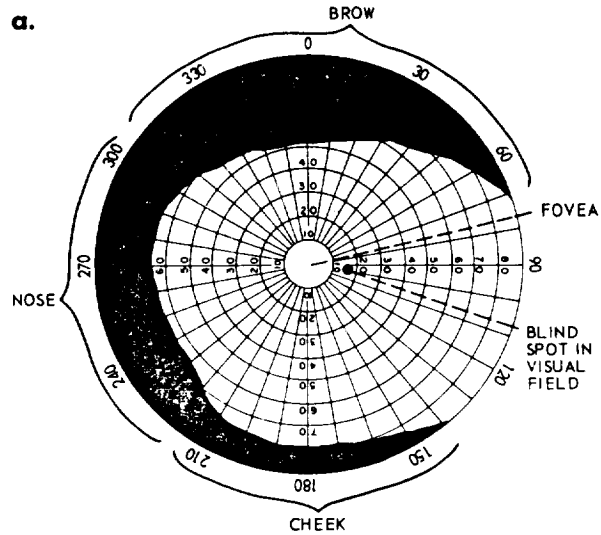
Figure 2-38

Monocular and Binocular Visual Fields

Figure a is a perimetric chart that shows the average monocular visual field for the right eye. Numbers are degrees; the eccentricity angle in degrees is the distance by which a target is displaced from the fovea. The head and eyes are motionless. The nasal field is to the left, and the temporal field to the right of the chart. Visual fields are mapped with a two-degree, achromatic circular target with a luminance of about 10 mL. Age (after 40 years) tends to narrow field limits. Errors of refraction (except presbyopia) have no significant effect on the size of the form field, but affect the size of color fields.

(After Ruch and Fulton. eds. [366])

a.



b.

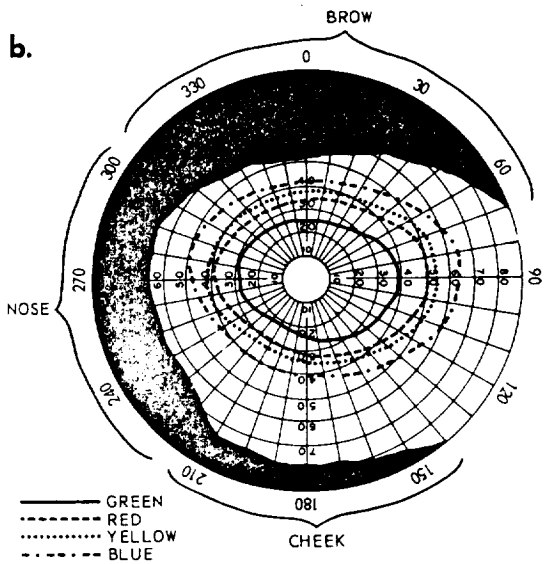


Figure b is a perimetric chart that shows average monocular visual field for both achromatic and chromatic targets for the right eye. The chart shows that the visual field for form is normally the largest; those for blue, yellow, red and green are successively smaller in the order given. A three-degree red target that is beyond 60° eccentricity will appear colorless; at 20° the target will appear as red. Increasing the brightness of the target or its size will tend to move color zones outward on the chart. Color fields are less stable than is the field for form.

(After Boring et al [64])

c.

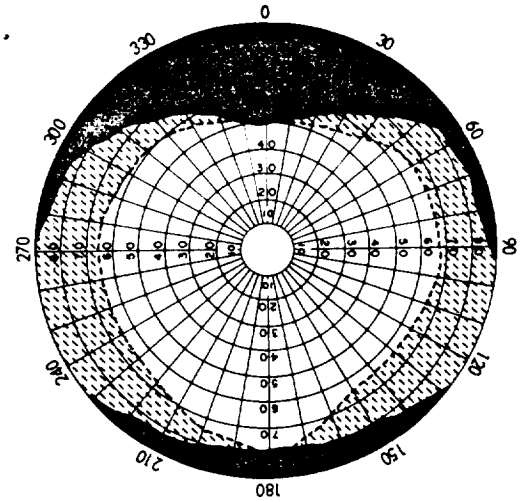


Figure c shows the normal field of view of a pair of human eyes. The central white portion represents the region seen by both eyes. The gray portions, right and left, represent the regions seen by the right and left eyes, respectively. The cut-off by the brows, cheeks, and nose is shown by the black area. Head and eyes are motionless in this case.

(After Ruch and Fulton, eds. [366])

visors will alter the field of vision and fields must be determined specifically for each design in question. (See recommendations below and Figure 16-24).

Movement Discrimination and Ocular Pursuit

Movement of a target relative to the background is a factor to be considered in detection of satellites in a starfield and in other ocular pursuit tasks. Figure 2-39 covers the ability to discriminate movement in the frontal (a) plane and in depth (b and c). Discrimination of movement in depth is a complex function of importance in docking and extravehicular activity. Figure 2-39b & c represents the basic data which may be converted to angular data for extrapolation to space conditions.

Figure 2-73 covers angular rate perceptions for small luminous targets in a starfield, specifically obtained for evaluation of visual satellite acquisition tasks in rendezvous.

Visual acuity is affected by motion (83, 296). Dynamic visual acuity is the recognition of details when the observer or the target or both are moving in comparison to the static visual actuity where all are fixed. As seen in Figure 2-40 dynamic visual acuity shows a predictable impairment with increasing angular velocity, starting noticeably to deteriorate with a speed rate of 20° per sec. The eye is unable to match the exact rate of movement of the object at greater speed, resulting in a motion of the image on the retina which reduces the contrast and thus the visual acuity. Peripherally, the impairment is more noticeable than centrally. In the case of a single target with increasing speed the deterioration first increases slowly then more rapidly. Decrement in visual acuity with motion is about the same when the subject or the object is moving and the other remains static (296). A higher dynamic visual acuity is obtainable when normal head movements are possible than when the head is fixed (111). Legibility criteria for moving alphanumeric symbols are available (266).

The masking effects of moving light stimuli on the luminance threshold of a stationary stimulus have been studied (276). False movements in the visual fields often result from vestibular and other illusionary phenomena (449). These will be covered in detail in Acceleration (No. 7).

Dark Adaptation

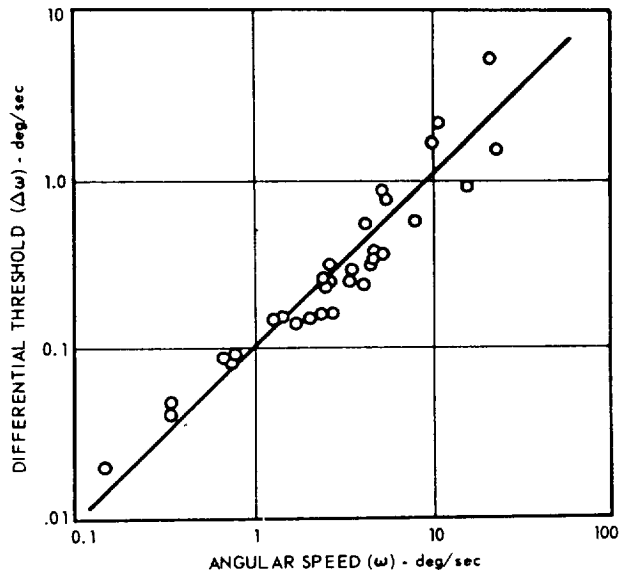
The eye becomes much more sensitive to light in darkness (231). Very little of this can be attributed to the dilation of the pupil shown in Figure 2-41 which is hardly enough to account for the many orders of magnitude of difference in sensitivity which occur when one adapts to darkness after exposure to a high illumination (76).

Another basis for the tremendous improvement of vision under dark adapted conditions is the fact that the concentration of photosensitive materials is increased. When the eye is placed in darkness, a concentration which was roughly in balance with conditions of illumination at a high level is

Figure 2-39

Discrimination of Movement

a. In the Frontal Plane



The differential threshold ($\Delta\omega$) is the amount that the angular speed of an object moving at right angles to the line of sight must change to be detected as a new speed. Data points shown on the graph are thresholds gathered from eight different experiments, for abrupt changes in speed from ω_1 to ω_2.

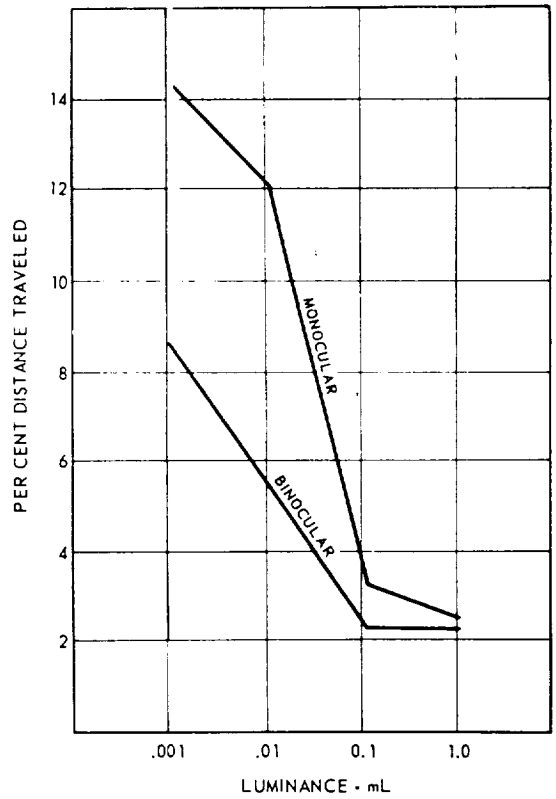
When an object stationary in the visual field ($\omega_1 = 0$) is suddenly set in motion, the minimum speed which is perceived as motion ("rate threshold") varies from 1 to 2 minutes of arc per second (0.017 to 0.033 deg/sec).

Threshold for movement in peripheral vision is higher than the threshold in central vision. Effects of illumination and contrast on differential threshold are imperfectly known at this time. The rate threshold is higher at low illumination levels and when no fixed visual reference is available.

(After White[446] Adapted from Brown[79] and Graham[178])

Figure 2-39 (continued)

b. In Depth



c. In Depth

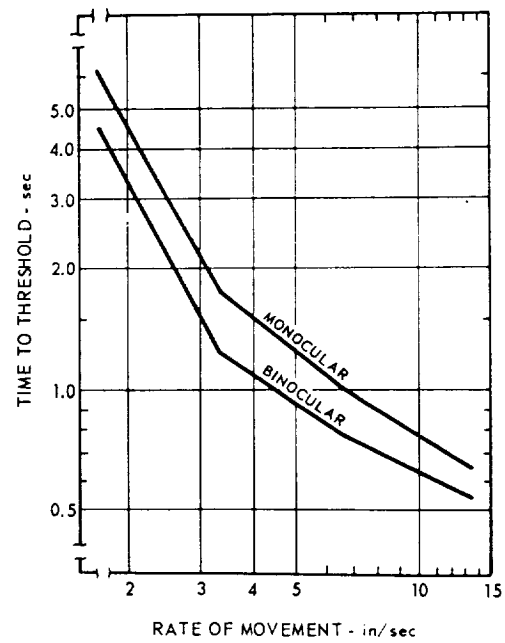


Figure b shows successful perception of movement in depth of a luminous target on a black field as a function of change in visual angle (per cent distance traveled) and of luminance. Figure c shows the time required to perceive movement in depth as a function of rate of change of visual angle (target speed). Both curves are for 75% correct responses, where 50% correct would be chance performance, since the target moved both toward and away from the observer, who had to choose the correct direction.

The target was a lamp measuring 3.5 inches in diameter which was moved back and forth on a track from an initial distance of 25 feet. At the initial distance, the lamp subtended a visual angle of 40 minutes of arc. A 2% change in distance, which was detected as movement at the higher luminance levels, represented a 2% change in visual angle, or a change of about 0.8 minutes of arc. The range of target speeds from 1.65 to 13.2 inches per second produced initial changes in visual angle from about .25 minutes of arc to 2 minutes of arc.

(After White[446] Adapted from Baker and Steedman[23])

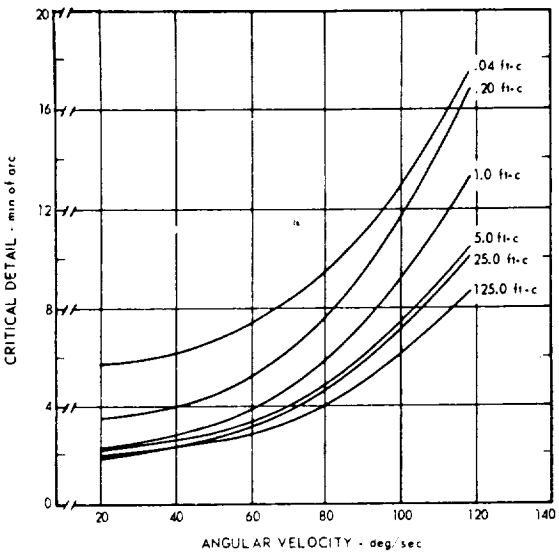
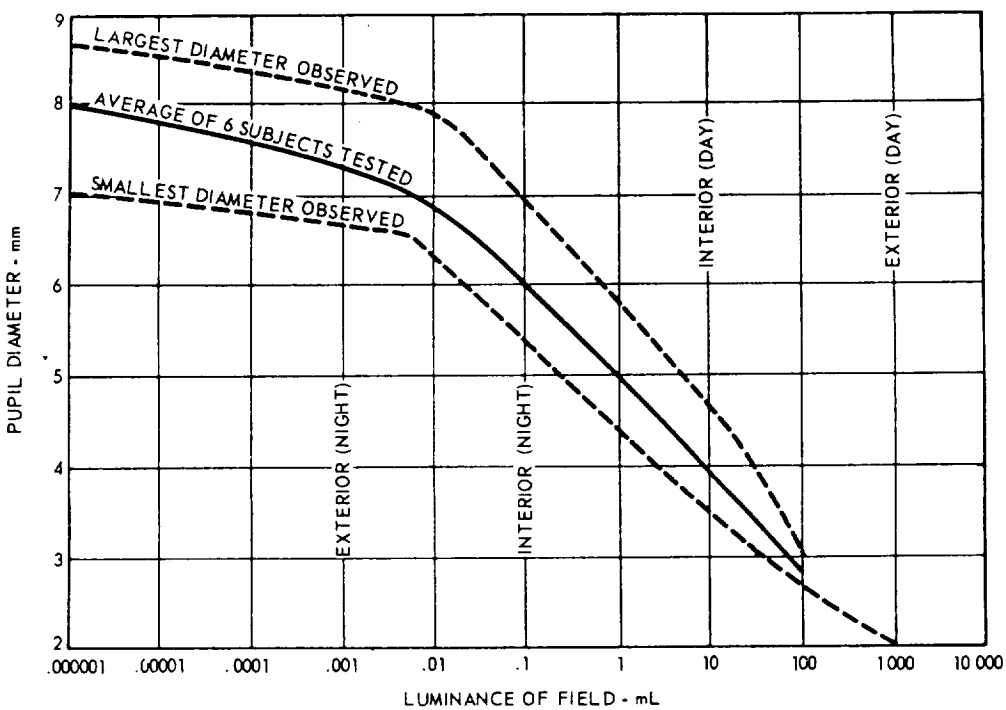


Figure 2-40.

Dynamic Visual Acuity
During Ocular Pursuit

The effects of increased angular velocity of rotation on visual acuity at each of six levels of illumination are shown in the graph. The relationship shown is for a black Landolt-ring on a white background. The data show that visual acuity declines progressively as angular velocity increases, and that acuity is benefited by increasing the illumination on the target.

(After White (446) Adapted from Miller(296))



There are a number of factors which affect the size of the pupil. The relationship shown here is diameter and variations in the luminance of a large uniform field. It is not possible at this time to predict the size of the pupil for non-uniform distributions of luminances in the visual field.

Figure 2-41

Pupillary Diameter and Luminance

(After IES Lighting Handbook(222))

supplanted by the much higher concentration which is found in the dark adapted eye. There is, however, a large change in sensitivity, many orders of magnitude, which takes place after more than 90% of the photo-sensitive materials have been regenerated (368). There is therefore, no direct relation between sensitivity and concentration. Other changes must also be occurring. One of the things which is probably occurring is a transition in the nature of the eye's capability of utilizing energy distributed over area. This is reasonable because the eye is not as capable of resolving visual detail in the dark adapted state and at low luminances. It would appear that spatial resolution capacity has been exchanged for sensitivity to flux level in the retina. The "critical duration" of the eye, the utilization time beyond which energy cannot be summated over time for the achievement of a given energy threshold level, becomes longer at lower levels of illumination. Increased sensitivity to flux is thus achieved not only at a cost of reduced spatial resolution apparently, but also of temporal resolution. The eye is not as sensitive to a pulsating light at lower luminance as it is at a high luminance. The higher the luminance, the faster the pulsation the eye can detect (Figure 2-36).

Light sensitivity at a given moment depends on the length of time the eye has been exposed to a certain level of illumination. Factors that influence absolute sensitivity to light are: (1) the duration of, and (2) average pre-exposure luminance, (3) the size, shape, contrast conditions and viewing time of the test object, (4) the color of the pre-exposure light and the test light in measuring sensitivity, (5) the region of the retina stimulated, and (6) physiological status of the individual (231). The data of any investigator must therefore be used with great caution in predicting dark adaptation under different conditions (389).

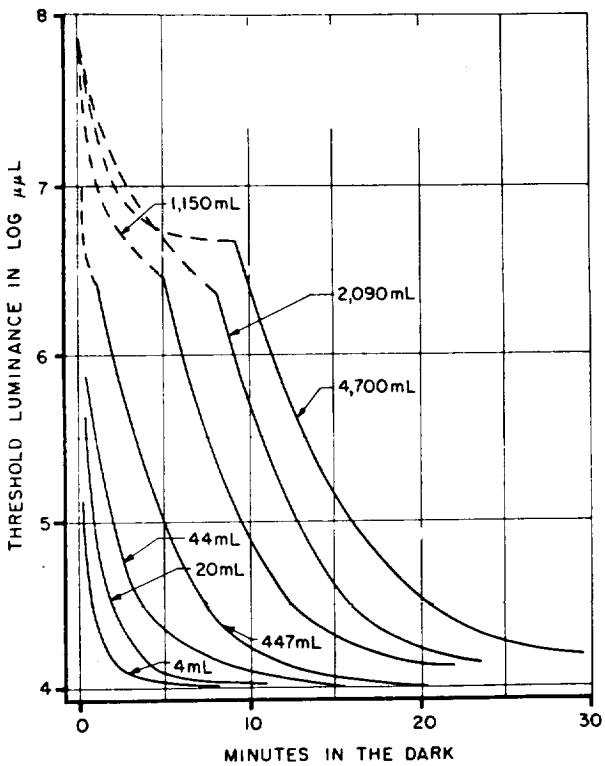
Figure 2-42 shows examples of several variables of prior exposure on dark adaptation. Rods and cones differ in the time factors associated with their activities: As shown by slope change in Figure 2-42a, the rods are much slower in action than the cones. The time required to adapt to a given threshold level is shorter when the pre-exposure brightness is lower, and when the pre-exposure light is composed of wavelengths in the red portion of the spectrum (Figure 2-42b and 2-42c). Note that the thresholds may differ by an order of magnitude depending on specific subjects and test conditions.

Figure 2-43 shows effect of test conditions on dark adaptation such as area of test object (210), wavelength of test stimulus (93), region of retina used (210) and population difference (388) - all under the specific conditions used in gathering the data. Hypoxia and nutritional state of subjects are major factors in dark adaptation (93, 231, 388, 424). The problem of optimizing cockpit color lighting for preservation of dark adaptation has received recent review (291, 389).

When the eye has been adapted to a given luminance, the luminance that is just visible immediately after is the instantaneous threshold. Figure 2-44 shows a plot of pre-adapting luminance in mL against the instantaneous threshold. The curve is a straight line except at the higher luminances where factors other than adaptation are present. This graph is for a square target that subtends 10 minutes of arc, and assumes that the observer is pre-adapted to a given wide field luminance. An observer adapted to a luminance of 1.0 mL

Figure 2-42

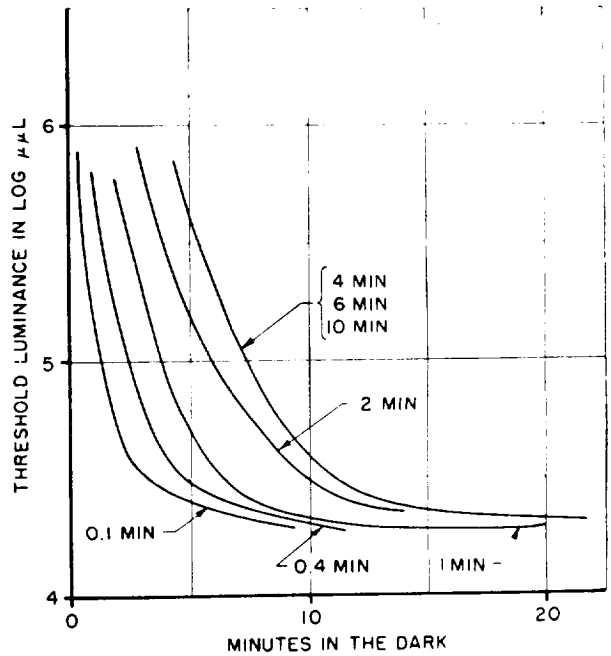
Dark Adaptation as a Function of Previous Light Exposure



a. Intensity of Previous Light

Dark-adaptation curves for one subject following exposures to lights of various luminances for four minutes. The broken lines indicate the color of the test light (violet) could be identified at threshold. The thresholds in this example are one order of magnitude higher than usually shown.

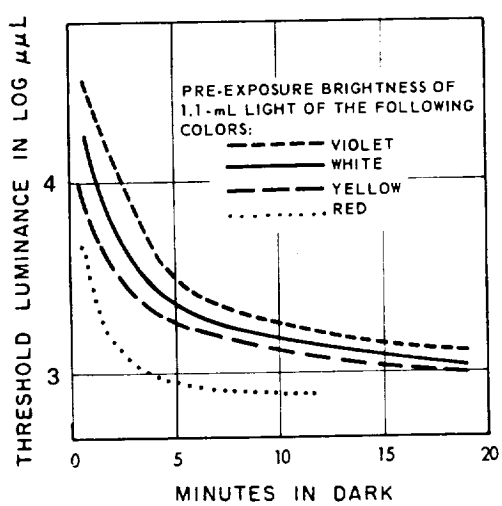
(After Chapanis [93] from Data of Haig[192])



b. Duration of Previous Light

Dark-adaptation curves for one subject following exposure to light of 447 mL for various durations. Only the rod portions of the curves are shown here. Thresholds are one order of magnitude higher than usually found.

(After Chapanis [93] from Data of Haig[192])

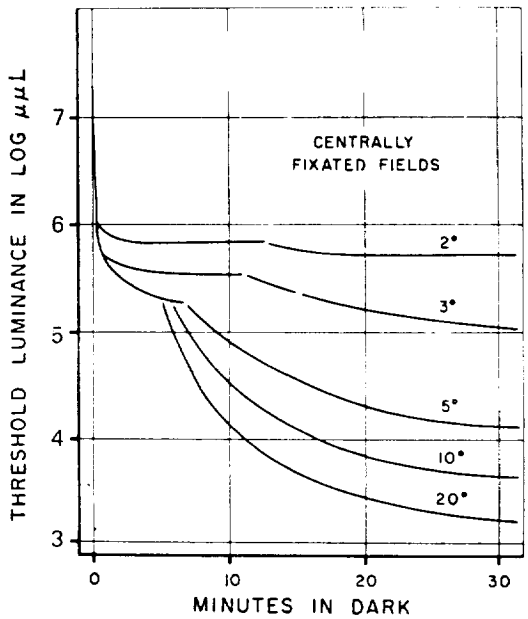


c. Dark Adaptation Curve as a Function of Color of Previous Light

(After Peskin and Bjornstad[339])

Figure 2-43

Dark Adaptation as a Function of Test Light Exposure



a. Area of the Test Object.

Dark-adaptation curves for centrally fixated areas of different size.

(After Bartley[29] from Data of Hecht et al[210])

b. Wavelength of the Test Stimulus

Dark-adaptation curves measured with lights of different wavelengths. Although lights were equated in brightness initially, they are no longer equally bright even at cone threshold. The differences are further exaggerated during rod dark adaptation.

(After Tufts Handbook[416] Data from Chapanis[93])

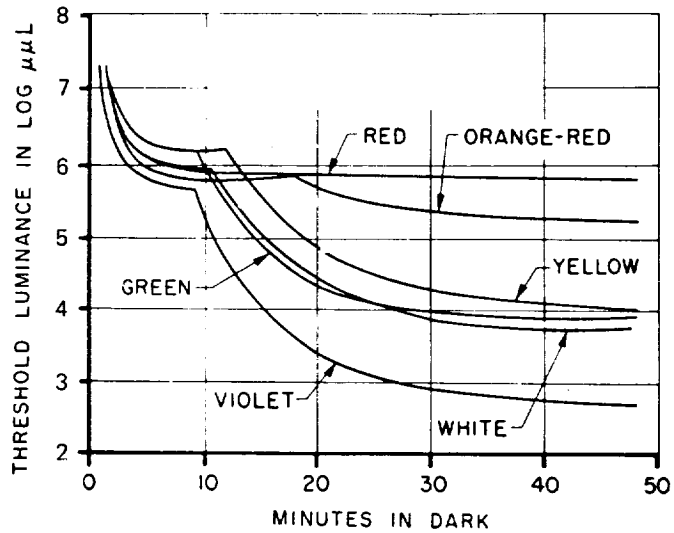
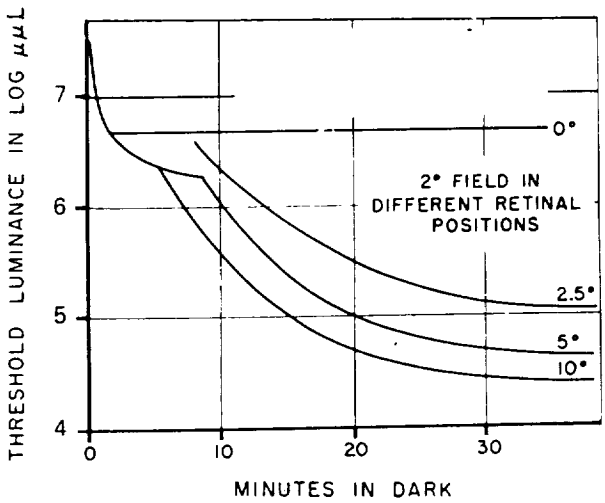


Figure 2-43 (continued)



c. Region of the Retina Stimulated.

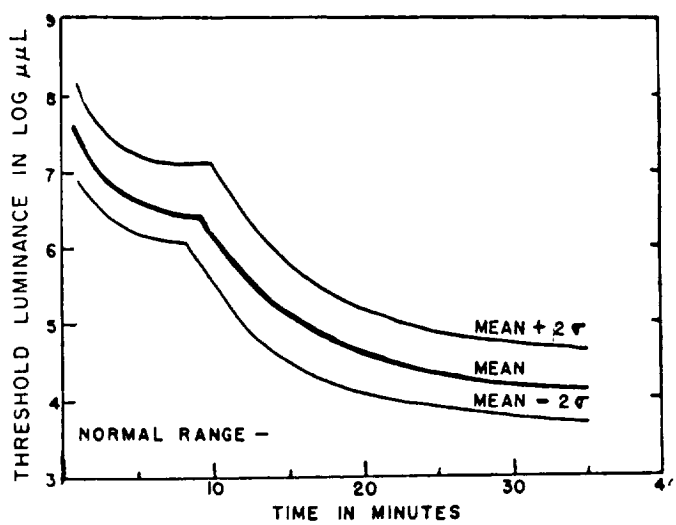
Dark-adaptation curves measured with a 2-degree test object placed at various angular distances from the fixation point.

(After Bartley[29] from data of Hecht et al[210])

d. Population Factor

Rate of dark adaptation after preadaptation to 1100 millilamberts. A 1-degree white test field located 15 degrees from fixation in nasal field. The area between the upper and lower curves includes 95 percent of those tested.

(After Sloan[388])



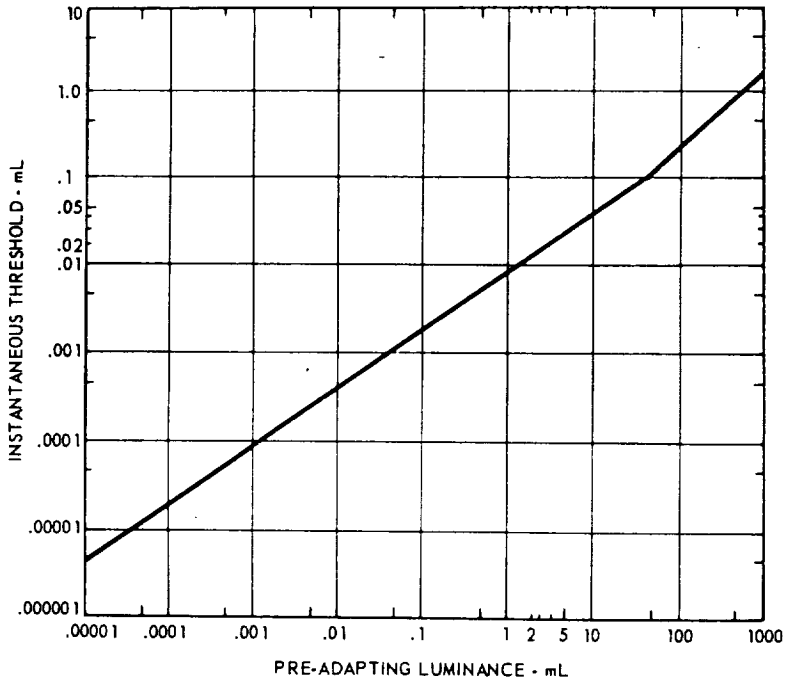


Figure 2-44

Instantaneous Threshold for Light

(Adapted from Nutting[322])

can see a 10 minute square target about one hundredth as bright immediately after the pre-adapting field is turned off. If the observer in question were exposed to a field luminance of 1000 mL but the target luminance was 0.0001 mL, the predicted luminance threshold in Figure 2-42a indicates he must wait about 10 minutes after entering a dark room before he can see the target light. Figure 2-44 is for simple light detection and does not permit a prediction of instantaneous visual acuity threshold, which requires discrimination of form. Dark adaptation data pertinent to cathode ray tube (CRT) displays are seen in Figures 2-67 to 2-69.

Training techniques may aid in optimizing night vision, especially during lunar surface operations (286, 417).

Glare and Flash Blindness Phenomena

Glare is defined as any degree of light falling upon the retina in excess of that which enables one to see clearly; that is, any excess of light which hinders instead of helps vision. Glare can be further differentiated into:

(1) Veiling glare: created by light uniformly superimposed on the retinal image which reduces contrast and, therefore, visibility
(2) Dazzling glare: adventitious light scattered in the ocular media so as not to form part of the retinal image
(3) Scotomatic or blinding glare (flash blindness): produced by light of sufficient intensity to reduce the sensitivity of the retina.

Although all three types of glare are present in the case of high-intensity light, the effects of the first two are primarily evident only when the source is present. The third type, scotomatic or blinding glare, is especially significant in flash blindness where it produces symptoms (afterimages) which persist long after the light itself has vanished. The afterimage is a prolongation of the physiological processes which produced the original sensation response after cessation of stimulation.

Glare

Regardless of whether the glare source is direct or indirect (reflected or specular), it can cause discomfort, or it can affect the visual performance, or it can do both. The visual discomfort or annoyance from glare is a common well-understood experience and has been confirmed by many experiments. In connection with certain experimental studies, it has been found that people sometimes become more physically tense and restless under glare conditions than under nonglare conditions.

In general, visual acuity is at a maximum when the eyes are adapted to the brightness level of the target and background. But acuity is reduced when the target and background are at a lower brightness than the greater surround. The curve in Figure 2-45 shows the effect of surround brightness both darker and lighter than the target and the immediate background (278). Acuity is best when the surround is a little darker than the target. Thus, it is suggested that for best acuity, targets should not be in a shadow or near a large area of much higher brightness. Recent reviews of surround brightness and size on visual performance are available (223, 224).

Visual acuity is best when the eyes have not been exposed to high levels of brightness. As a general rule if visual displays have to be read by people who have just been exposed to high levels of brightness (the open sea, clouds, desert, or snow), the level of brightness of the displays should be higher than would normally be necessary - they should be at least 0.01 as bright as the pre-exposure field (see Figure 2-44).

From a practical standpoint, data are available which provide a basis for specifying increased display contrast requirements when the area surrounding the display is substantially brighter than the background within the display.

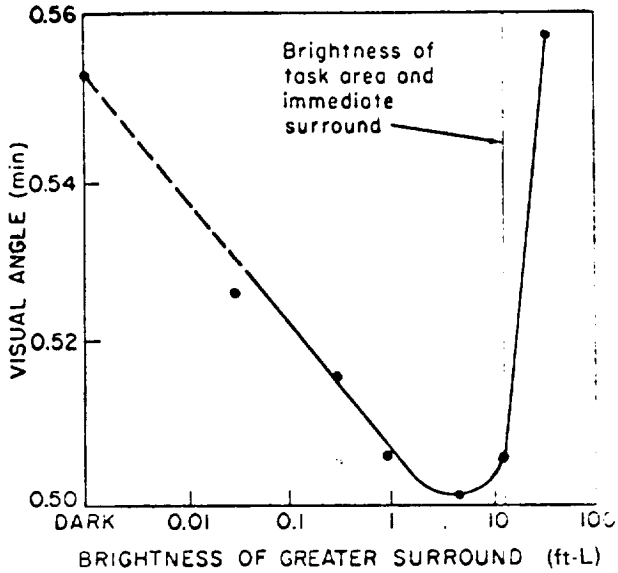


Figure 2-45

Threshold Visual Angle as Determined by Brightness of the Greater Surround.

(After Lythgoe [278])

Under these conditions, the contrast threshold is fairly sensitive to the surround-to-background ratio. The increase in a subject's contrast threshold appears to be proportional to the increase in surround brightness. This conforms to findings with point glare sources whose effects also appeared to be proportional to their brightness (219). For threshold contrast with a given background brightness, surround-to-background brightness ratios greater than "one", and background angles in the 5° - 45° range, the following empirical formula fits the experimental data fairly well (±10%): (224)

$$C' = C_{ref}\left(0.9815 + \frac{0.0185\ BS}{BB}\right) \qquad (3)$$

where C' = threshold contrast for a given ratio, $\frac{BS}{BB} > 1$

C_{ref} = threshold contrast when $BS/BB = 1$

BS = surround brightness

BB = background brightness

The experimental results show some evidence suggesting that surrounds considerably darker than the background also adversely affect visual performance, i.e., raise the contrast limen. (See Figure 2-45.)

Changing background angle, which determines the proximity of the inner edge of the extended surround to the stimulus object, over a range of from 5° to 45°, even with the highest surround-to-background brightness ratios, appears to have a surprisingly small effect upon the contrast limen (224). The change in threshold is much smaller than that predicted on the basis of experimental results obtained by others using point sources of glare (219, 302). However, findings concerning background angle effects must be interpreted with caution since background angle was only varied from session to session rather than during a given session as was the surround-to-background

brightness ratio. There is reason to believe that factors other than the experimental variables contributed substantially to day-to-day variability. Also some tasks may be more strongly affected by background angle than others.

A log-log plot of contrast threshold versus background brightness (BS/BB = 1) showed a very nearly linear relationship over the background brightness range of from 0.17 mL to 18.43 mL (to 129 mL for one subject) tested. The following formula expresses this relationship for the mean data:

$$\log C_{ref} = -0.368 - 0.253 (\log BB) \qquad (4)$$

where C_{ref} = Contrast limen (for BS/BB = 1)

BB = Background brightness

(BS = Surround brightness

While the effect of glare on visual performance can be of serious consequence by itself, the visual discomfort brought about by glare can also be a matter of some concern. Though the cause is physical, the discomfort brought about by it is often of a subjective nature. The evaluation of discomfort, then, must make use of subjective responses as criteria (13,189 , 190,272).

Involved in such procedures is the concept of the "borderline between comfort and discomfort" (BCD) (272). The variables which govern whether a visual environment is comfortable or not include two groups. First are those that are basic to the situation, such as brightness of the (glare) source or luminous area, its visual size, and the brightness of the surrounding field or area and adaptation brightness. Second are certain factors that have a modifying effect, including the position of the source in the visual field, the number of sources in the visual field, and their configuration and arrangement. Indices of discomfort related to these variables are available (155, 191).

The effect of angle of the glare source relative to the visual axis on visual performance has received study (273,278). Sudden glare in the line of sight under conditions of low brightness background has received much study for highway illumination (346). Many of the findings are pertinent to the space environment. They are summarized in Figure 2-46a to d where comparison is made of several studies of glare sources presented on line of sight (219,272 , 323). Figure 2-46a and c show the variation expected under different experimental conditions. Figure 2-46b indicates that the equation relating the BCD to adaptation brightness (F) varies as the angular size of glare source in steradians. The equations are of the general form:

$$B = aF^b \qquad (5)$$

where B = BCD in footlamberts

F = adaptation brightness in footlamberts

Q = source size in steradians and determines values of a and b

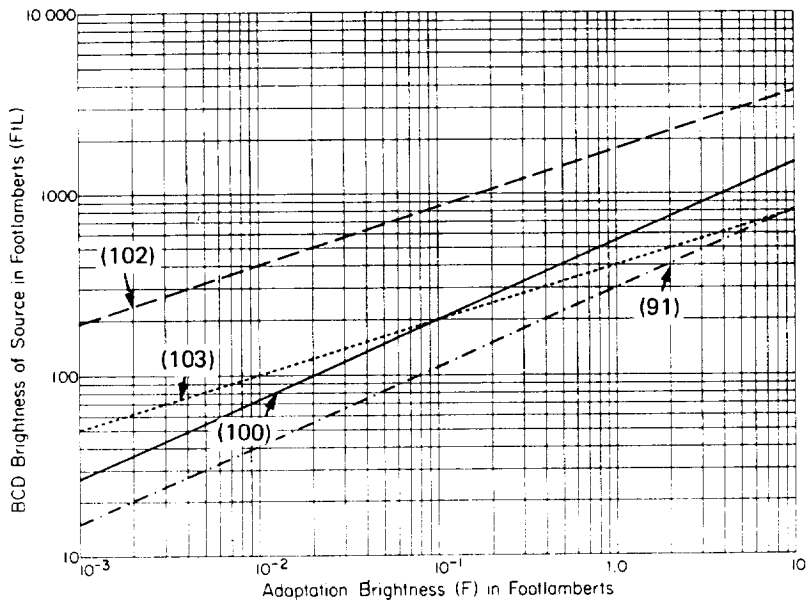


Figure 2-46a

Comparison of the Results of Various Researchers for a Source Size (Q) of 0.0011 Steradian. The Sources Are Located on Line of Sight.

(After Putnam and Faucett[346])

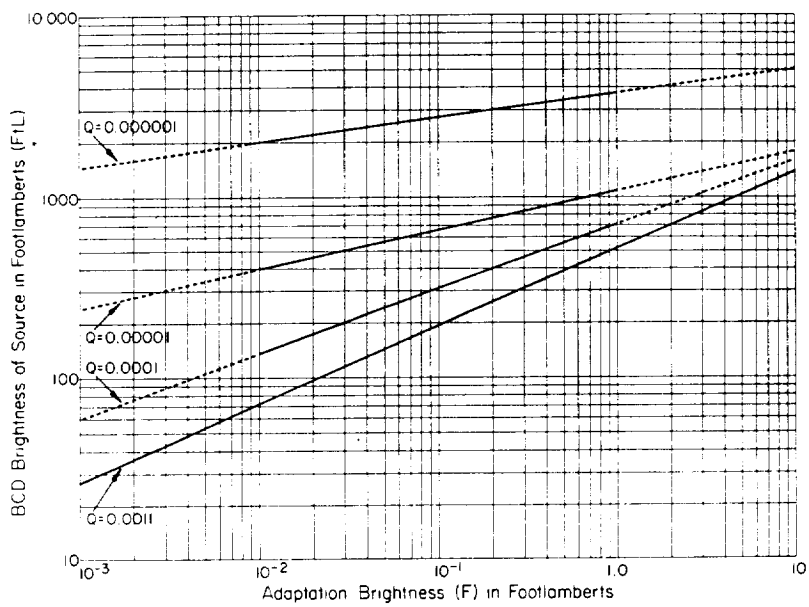


Figure 2-46b

The Relationship Between BCD Brightness of a Source and Adaptation Brightness (F). The Source Is on the Line of Sight and Subtends a Solid Angle of Q Steradians

(After Putnam and Faucett[346])

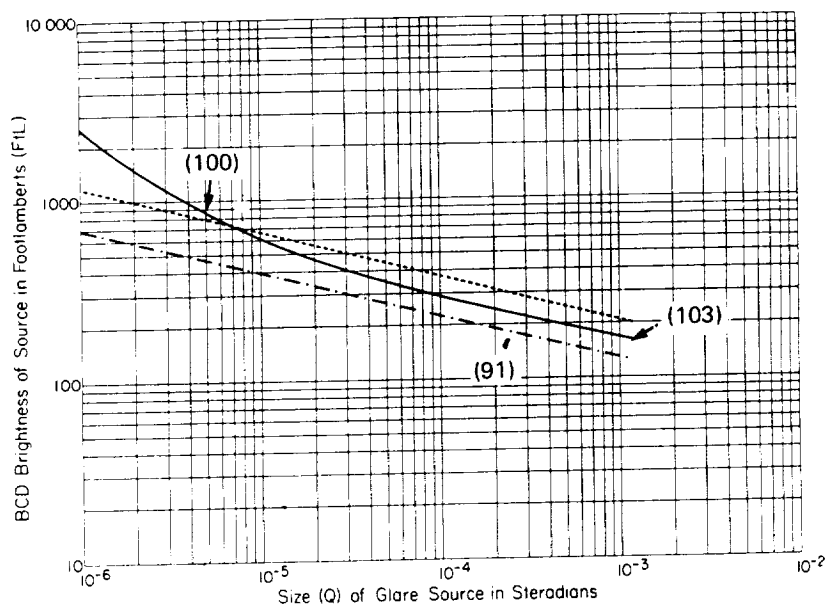


Figure 2-46c

Comparison of the Results of Various Researches for an Adaptation Brightness of 0.10 Footlambert. The Sources Are Located on Line of Sight.

(After Putnam and Faucett[346])

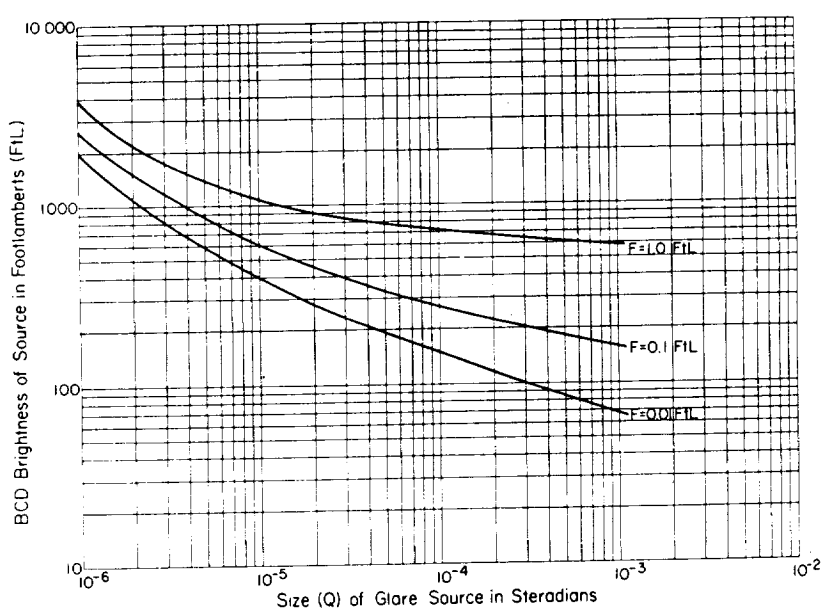


Figure 2-46d

The Relationship Between BCD Brightness and Size of Source for Three Different Adaptation Brightnesses. The Sources Are Located on the Line of Sight.

(After Putnam and Faucett[346])

$$B = 529F^{0.44} \qquad (Q = 0.0011)$$
$$B = 734F^{0.36} \qquad (Q = 0.0001)$$
$$B = 1115F^{0.23} \qquad (Q = 0.00001)$$
$$B = 3759F^{0.14} \qquad (Q = 0.000001)$$

When these data are plotted for a constant adaptation brightness (F) the curves in Figure 2-46c and 2-46d result. These curves can be represented by the following equations. These equations are all in the general form:

$$B = aQ^{-b} + c \qquad (6)$$
$$B = 0.68Q^{-0.60} + 531 \quad (F = 1.0)$$
$$B = 0.43Q^{-0.62} + 124 \quad (F = 0.1)$$
$$B = 0.16Q^{-0.68} + 53 \quad (F = 0.01)$$

The brightness (B) at the borderline between comfort and discomfort is therefore a complex function of the adaptation brightness (F) and the size (Q) of a source when F varies from 1.0 to 0.01 footlamberts and Q from 0.0011 to 0.000001 steradian. The experimental results show that the BCD brightness in these ranges of adaptation brightness and source size does not vary linearly as would be indicated by extrapolations of several investigations (Figure 2-46c). As the glare source becomes smaller than 10^{-5} steradian, the BCD brightness of the glare source becomes greater at an increasing rate, indicating that very high brightnesses may not be uncomfortable if the source is extremely small. Such data are of importance in evaluating glare effects on the Earth, in orbit, and on the lunar surface. In the presence of a non-scattering vacuum the relative effects of glare in distorting the usual cues for depth and size, perception and rate of closure may be altered (367, 410). This will require further study.

Irradiation Phenomena

An observer attempting to measure the boundary between a bright area and a darker area will perceive the boundary to lie toward the darker area. Astronomers refer to this effect as "irradiation" and define it in operational terms as the spreading of a bright image on the retina of the eye making the diameter of any bright object to appear to be larger than it really is (30 , 415).

The magnitude of the effect of irradiation on astronomical angular measurements with optical instruments varies with the luminance of the bright limb, the contrast of the bright limb against the background, the optical system used, the dark adaptation of the observer, and the individual observer. In astronomy, corrections for irradiation are empirical and are derived from performance records of experienced observers. For example, the Nautical Almanac uses an irradiation correction of 1.2 minutes of arc for measurements of the altitude of the upper limb of the Sun with the marine sextant.

Several investigations have been performed which are related to the problem of visually sighting a space vehicle near the sun (104, 105). Measures of the minimal angle of resolution (MAR) for two small self-luminous objects against an unilluminated background have also been studied and have indicated that MAR tends to increase as a function of object luminance. For two point sources against different background illuminations, the MAR was found to depend entirely upon contrast and not upon the absolute value of background luminance (325). The MAR increases linearly as a function of the logarithm of the luminance ratio from an I_s/I_b of 100 to at least 5×10^4. The MAR associated with the highest contrast ratio in this study was found to be 4.0 minutes of arc for glare-source luminance of 4000 ml at a background of 0.07 millilamberts. At luminance ratios of less than 100, the MAR is constant at about 1.8 minutes of arc.

Other of the visual variables involved in celestial navigation will be greatly affected if the observer looks at or near the sun or other intense source. Perception of a moving point source in close proximity to a source of high luminance and the correspondence between physical form and perceived shape are factors to be considered in such a task. The variables include (1) glare-source shape, (2) glare-source intensity, (3) point-source direction of movement in eight frontal-plane meridians, and (4) point-source direction within each meridian. In a recent study of this important problem, five highly trained observers viewed a stimulus configuration through an artificial pupil which provided a 10-1/2° field of view (194). The moving "star" was used as a test spot to determine the characteristics of the luminous field gradient produced by the glare source of only 4250 ft L. It was found that the distance, in visual angle, from the perceived edge of a glare source at which a star disappears (or reappears) is directly related to the luminance of the glare source. This appears to be a curvilinear function which accelerates rapidly at about 1000 ft L and again begins to decelerate at about 4000 ft L as shown in Figure 2-47.

This finding is somewhat greater than those obtained for two point sources (325). The star disappears and reappears at different apparent distances from the edge of the glare source, depending upon what kind of edge geometry exists. An example of a straight edge can be found on the sides of the square and triangular mirrors. The edge of the circular mirror provides an example of a curved edge. The star disappears and reappears farther from the curved edges than it does for straight line edges under equivalent luminance conditions. Figure 2-48 presents these data.

The irradiation phenomenon results in distortion of shapes of the object (194, 367). The apparent size of the glare source increases as a function of its luminance. This effect can also be seen in Figure 2-49. The response variance tends to be larger under the higher luminance conditions than under lower luminance conditions; however, variance does not appear to be significantly affected by either the shape of the glare source or the meridian of travel of a test star (194).

It can be concluded that as a result of the irradiation phenomenon, (1) navigational sightings should be confined to a vision envelope which does not include any extremely bright sources aimed in the direction of the eye.

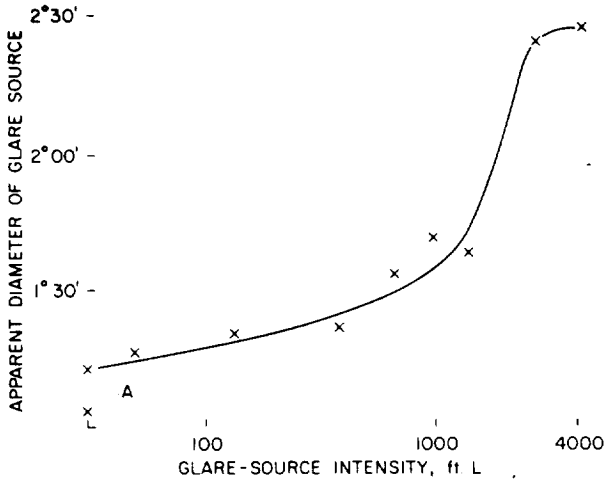
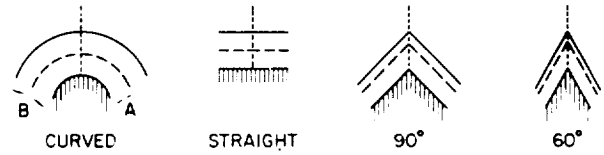


Figure 2-47

Effect of Glare Source Intensity upon Its Apparent Size.
Note: A zero intensity or control condition

After Haines[194])



----- PATH OF POINT SOURCE
—— FULL INTENSITY
-- 0.4 LOG INTENSITY

EDGE GEOMETRY	VISUAL ANGLE	
	B	A
CURVED (16)*	12' 29.3"	6' 26.8"
90° (8)	8' 26.7"	5' 36.1"
60° (6)	8' 35.7"	6' 41.1"
STRAIGHT (14)	7' 33.8"	3' 31.8"

* INDICATES NUMBER OF SETS OF SIX IN AND SIX OUT TRIALS EACH VALUE IS BASED UPON

Figure 2-48

Effect of Glare-Source Edge Geometry Upon Point Source Disappearance and Reappearance Position.

(After Haines[194])

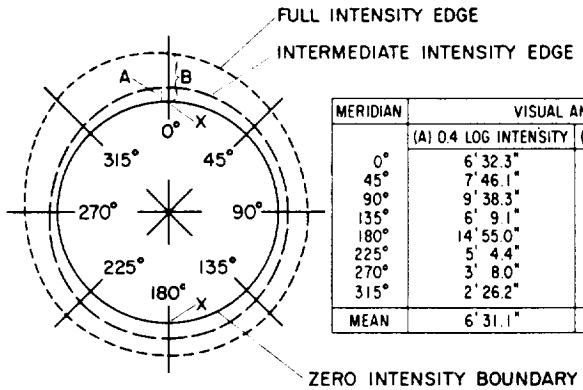
(2) Visual identification of highly luminous objects in space, on the basis of their shape, may lead to incorrect identification. (3) If navigational sightings are performed using high luminance sources as reference objects of approximately 2000 ft L apparent luminous intensity or greater, one must expect rather large errors in estimating star eclipse angles (from the edge of the luminous source). (4) Under high luminance conditions one is likely to perceive size and shape characteristics of the glare source which may misrepresent the actual glare producing object. (5) If a star is going to be chosen as a navigational referent with respect to either the perceived edge of the sun's photosphere, which is unlikely, or some man-made object having a high luminance (direct or reflected), optical filters will have to be used to reduce the photic flux to such a level that the physical edge of the referent can be accurately perceived (86 , 242 , 332).

The recovery time after relatively prolonged exposure to low levels of glare in highway situations has received quantitative study (234). Similar studies are required to confirm the reciprocity law under conditions of lunar and extravehicular operations. The data for exposures of short duration presented below should not be directly used under such conditions.

Flashblindness

In flashblindness the afterimage is essentially a temporary blind area or scotoma in the field of vision. In spacecraft, this could be produced by the flash following meteoroid penetration (365). The time duration of this blind area is proportional to the intensity and duration of the light exposure. The greater the intensity and/or the longer the duration of exposure, the more intense and, to a certain extent, the more persistent the afterimage. Ordinarily, the sequence of events following stimulation of the retina by a flash of

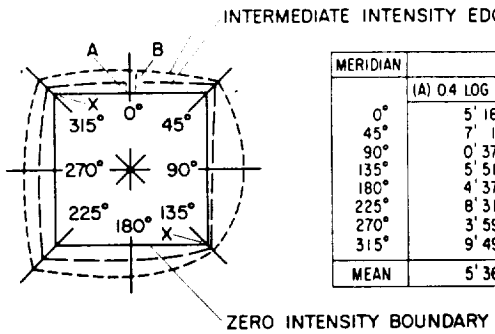
(CIRCLE)



MERIDIAN	VISUAL ANGLE	
	(A) 0.4 LOG INTENSITY	(B) FULL INTENSITY
0°	6' 32.3"	20' 35.9"
45°	7' 46.1"	13' 16.5"
90°	9' 38.3"	12' 39.2"
135°	6' 9.1"	12' 47.0"
180°	14' 55.0"	13' 8.0"
225°	5' 4.4"	12' 26.6"
270°	3' 8.0"	13' 8.0"
315°	2' 26.2"	20' 33.0"
MEAN	6' 31.1"	14' 29.5"

X-X DISTANCE = 1° 33' 13.3"

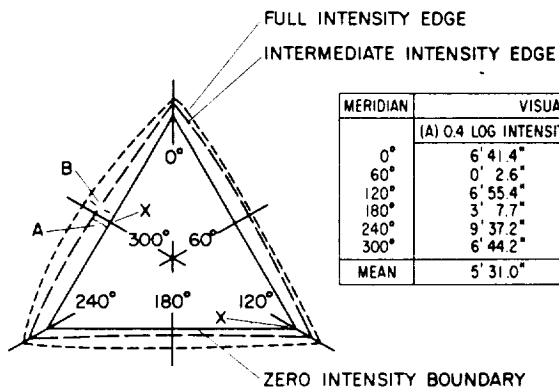
(SQUARE)



MERIDIAN	VISUAL ANGLE	
	(A) 0.4 LOG INTENSITY	(B) FULL INTENSITY
0°	5' 16.3"	8' 59.2"
45°	7' 1.8"	7' 57.4"
90°	0' 37.9"	12' 3.3"
135°	5' 51.5"	8' 50.0"
180°	4' 37.6"	11' 7.8"
225°	8' 31.4"	14' 9.2"
270°	3' 59.7"	9' 22.4"
315°	9' 49.1"	14' 18.3"
MEAN	5' 36.6"	10' 31.2"

X-X DISTANCE = 1°24' 59"

(TRIANGLE)



MERIDIAN	VISUAL ANGLE	
	(A) 0.4 LOG INTENSITY	(B) FULL INTENSITY
0°	6' 41.4"	6' 58.3"
60°	0' 2.6"	8' 0.8"
120°	6' 55.4"	10' 8.7"
180°	3' 7.7"	7' 15.7"
240°	9' 37.2"	11' 5.1"
300°	6' 44.2"	13' 34.8"
MEAN	5' 31.0"	9' 22.2"

X-X DISTANCE = 1° 30' 50.7"

Figure 2-49

Effect of Glare-Source Luminance Upon Perceived Size and Shape of Circles, Squares, and Triangles.

(After Haines[194])

light is the primary sensation of light followed by a series of positive and negative afterimages. With moderate light intensities, afterimages are not noticed because of the complex action of successive stimulation and continuous movement of the eye. However, if the original stimulation is of sufficient duration and intensity, the sensation will persist with an intensity adequate to reduce or entirely obliterate foveal perception until the effect is dissipated. This is the primary factor in flashblindness. Papers from a recent symposium on the loss of vision from high intensity light are now available (2).

The amount of visually effective light entering the eye, because it is an indication of the amount of photopigment bleached, seems to be the essential factor in the formation of the afterimage (63 , 95 , 297). A useful unit for specifying the amount of visually effective light is the troland-second, because it includes the area of the eye pupil and has the dimensions of retinal illuminance assuming perfect ocular transmission (see Table 2-2). The data may also be presented as cal/cm^2 at the retina. A glossary of radiometric and photometric concepts used in flash blindness and retinal burn research is available (19).

Attempts have been made to relate the intensity of light flashes to the alterations in sensitivity of the dark-adapted eye. At relatively low illuminances of less than 50 lumens/ft^2, there is found no alteration in the course of dark adaptation and a general correlation with the reciprocity law for momentary losses of sensitivity (10 , 400). The reciprocity law indicates that within certain limits L x T = K when L is in units of luminance of the dazzle and T is the duration of the dazzle. At a light source of moderate intensity, validity of the law has been confirmed (110, 154 , 248). The law appears to hold up to 30,000 m-L-sec. Above this level the effect of intensity factor becomes relatively greater than duration (306). Also, for energy in the range of 3 x 10^7 troland-sec., reciprocity appears to fall; flash durations of 1 millisecond being less effective than longer flashes (298). Theories on reciprocity failure have been presented (458).

In establishing criteria for visual recovery time after exposure to flash, there is some difficulty in comparing the results of different investigations, because the recovery times depend on the total effective integrated energy in the flash, the duration of the flash, the size of the critical detail in the target used to determine the recovery, and the luminance of the target. The pulse shapes may also be an important factor for the very long durations. The recovery time of visual performance following high-intensity flashes is related to the decay of the afterimage brightness which is a function of the amount of photopigment bleached by the flash. The afterimage reduces the perceived contrast of a visual display in the same manner as the addition of a uniform luminance over the display (297).

Figure 2-50 summarizes data from several studies on effect of flash energy in lambert-seconds and recovery time for perception of targets at two different levels of target illumination. These are higher than the usual instrument illumination levels in night vision (Table 2-60 and Refs. 231).

Figure 2-51 represents the effect of target luminance on recovery time after different flash energies.

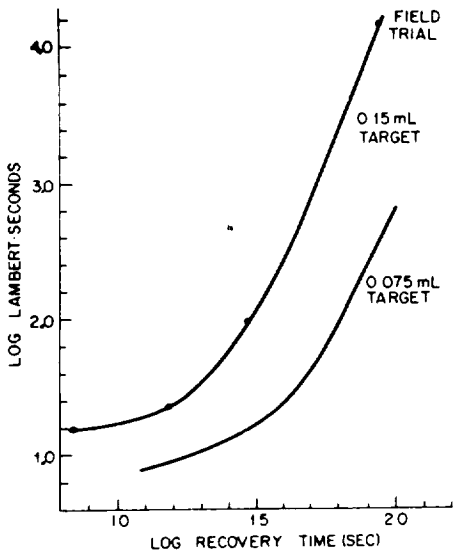


Figure 2-50

The Relationship Between the Logarithm of the Recovery and the Logarithm of the Flash Energy in Lambert-Seconds. Upper Curve from Whiteside[447] and Lower Curve from Metcalfe and Horne[292] for a Carbon Arc Source.

(After Miller[297])

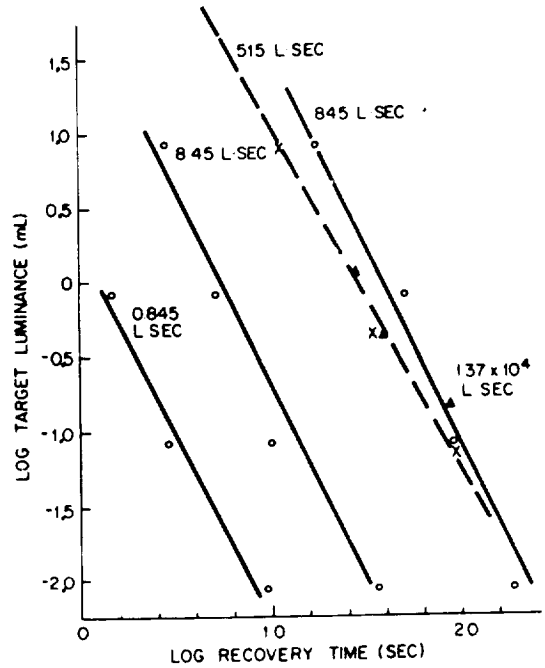


Figure 2-51

The Relationship Between the Logarithm of the Recovery Time and the Logarithm of Target Luminance. 0 - 0 from Russell[369], x - x from Metcalfe and Horn[292], and Δ from Whiteside[447].

(After Miller[297])

The recovery times following a flash appear to depend on the type of target used for measuring visual performance. There is an approximately linear relationship between the logarithm of the recovery time and the logarithm of the target luminance from 130 mL to 1 mL for the Snellen letters following high-intensity flashes. For luminances below 1 mL, the recovery times became increasingly longer than the simple relationship would predict. This is seen in Figure 2-52 where recovery times at different equivalent illuminance levels for targets of different sizes after varied levels of effective light energy impinging on the retina. Recovery time is measured as the time interval from flash to the first correct letter response in two successive correct responses. The recovery times for the detection of various targets and target luminances can be generalized by specifying the equivalent field illuminance for threshold of the targets. The equivalent field illuminance is the retinal illuminance required for threshold detection of the targets when they are viewed against a uniform field.

There is a linear relationship between the logarithm of the recovery time and the visual acuity for different size Snellen letters expressed as the reciprocal of the critical detail in minutes of arc. The effect of target size is seen in Figure 2-53.

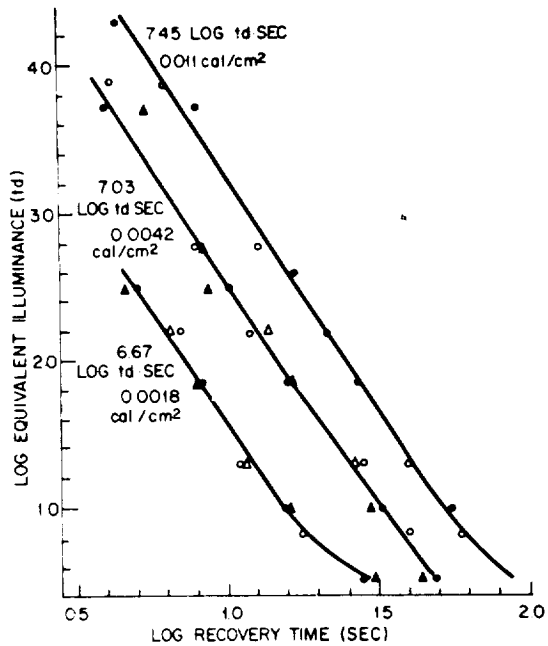


Figure 2-52

The Relationship Between the Log of the Recovery Time and the Log of the Equivalent Field Illuminance for Different Flash Energies Hitting the Retina (td sec or cal/cm^2). Open Symbols Are Times for a 28.4 Minute Letter; Closed Are for 16.2 Minute Letter. Circles Are for 1.4 msec. Flash with Luminance Varied; Triangles Are for Constant Luminance, Duration Varied.

(After Miller[297])

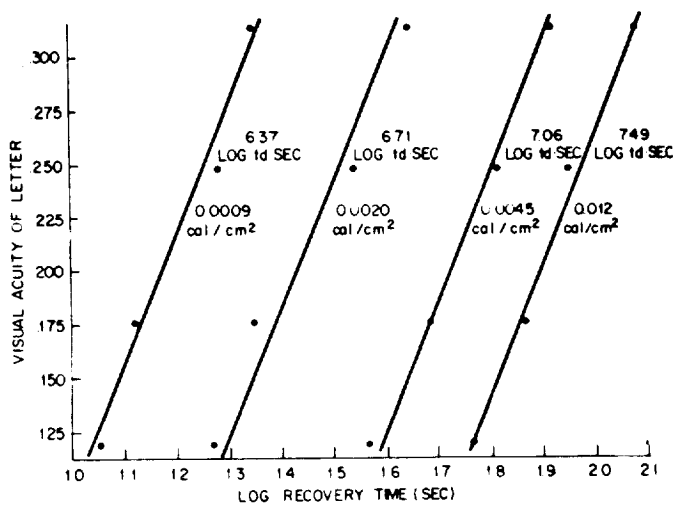


Figure 2-53

Log Mean Recovery Times for 4 Subjects for Various Letter Sizes at 0.07 mL.

(After Miller[297])

There is variability from subject to subject in the slope of the recovery function (378, 379). The pupillary factor is demonstrated as seen in Figure 2-54. Figure 2-41 gives expected pupillary diameters for different luminance levels.

The data derived from many sources for the size of the retinal image of a point source are plotted in Figure 2-55a as a function of the pupil diameter. It is evident from Figure 2-55a that the data obtained lack reliability. To be safe, one best assume the course indicated by the dotted line, which means a blur disc of almost constant size, namely 1 min of arc up to pupil diameters of 6 mm. Pupil diameters below 2 mm rarely occur; above 6 mm the increase in incident light hardly produces an increase in retinal light concentration as the light from the pupil border is so badly focused.

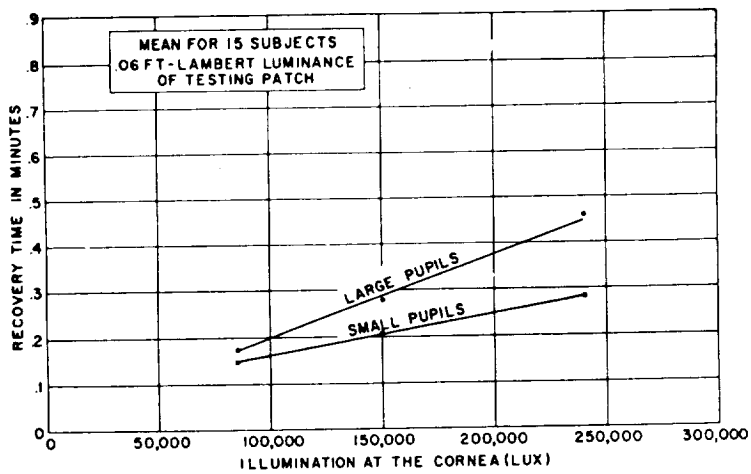


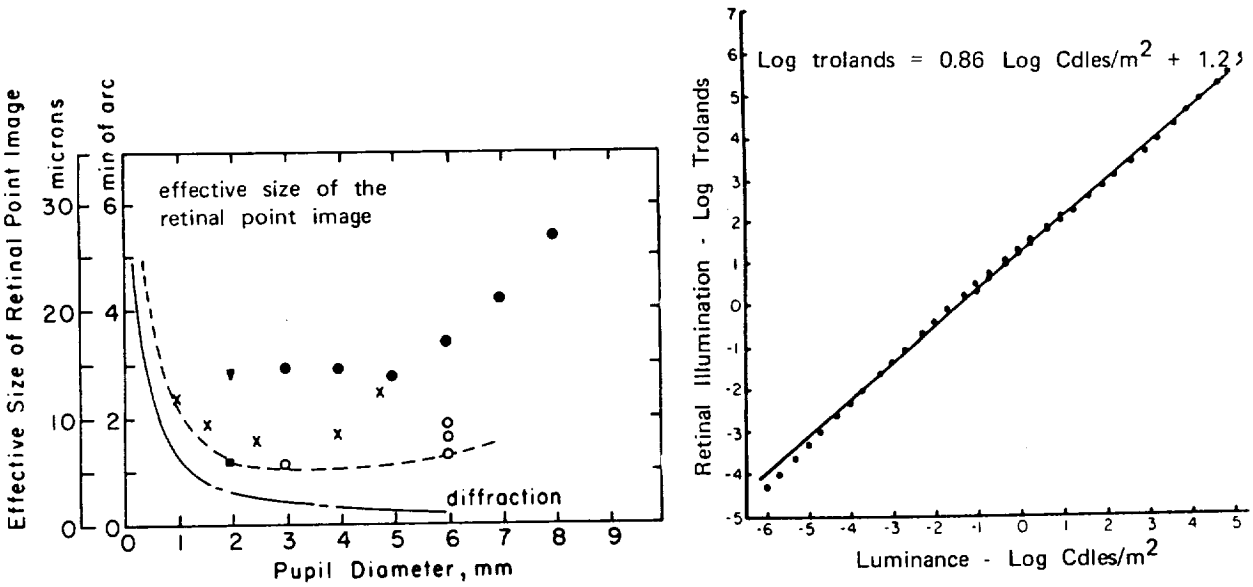
Figure 2-54

Effect of Pupil Diameter on Recovery Times (Mean of 15 subject). Luminance of Testing Patch was 0.06 ft-lambert.

(After Severin et al[379])

Figure 2-55

Retinal Illumination and Image Size Under Different Pupillary and Ambient Light Conditions.



a. The Minimum Size of the Retinal Image of a Point Source as Derived from Several Investigations (See text)

(After Vos[430])

b. Retinal Illumination as a Function of Luminance.

(After Hill and Chisum[216] and from data of LeGrand[260])

Retinal illumination as a function of the luminance of the visual field with pupil size taken into account is shown in Figure 2-55b. The retinal illumination changes only 0.86 log unit for each log unit change in luminance of the visual field.

Other recent findings are available and can be summarized (297): The only wavelengths of radiation in the flash that influenced the recovery times for foveal performance were those in the visible region. Infrared beyond 850 nm had no effect on recovery following the flashes, even when it accounted for more than 50% of the total flash energy. There is no significant cumulative effect on recovery times with successive flashes after the second flash when they were presented at intervals of 3 or 4 minutes. There is a small but statistically significant effect on foveal recovery times for different flash-field diameters from 2.5° to 10°. The smaller fields produced longer recovery times of the order of 10%. Preadaptation to relatively high-luminance levels lengthens the recovery time in proportion to the amount of photopigment bleached by the preadaptation. The amount of pigment bleached by the flash will be in addition to that caused by the adapting luminance.

Attempts have been made to write equations for visual recovery times after flash exposure. One equation appears to afford the best fit for all observers. This was an equation of the following form (75):

$$t - t_0 = a + b/(\log B - \log B_0) \qquad (7)$$

where t = perception time in seconds

t_0 = 0.20 sec for all conditions of adaptation

B = display luminance in ft L

B_0 = minimum luminance at which the display can be perceived under optimum conditions.

(-1.4 log ft L for visual acuity of 0.26;

- 2.3 log ft L for visual acuity of 0.08.)

Perception time t must approach a minimum t_0 as display luminance B is increased, and it may safely be assumed that a value B will be reached beyond which there will be no further reduction of t. If this is the case, then the constant, a, must be of the following form:

$$a = -b/(\log B_{max} - \log B_0) \qquad (8)$$

where B_{max} is the luminance at which t_0 is reached.

Assuming a value of 2.7 for $\log L_{max}$, equations (7) and (8) can be combined and rewritten as follows:

$$t = 0.2 + b \frac{(2.7 - \log B)}{(\log B/B_0)(2.7 - \log B_0)} \qquad (9)$$

It was found that the logarithm of b is proportional to the logarithm of A for data representing both of the two acuity levels, where A represents adapting flash energy in ft L sec. A simple power function therefore serves to relate b to A:

$$b_{0.08} = 0.108A^{0.58} \tag{10a}$$

$$b_{0.26} = 0.022A^{0.68} \tag{10b}$$

The difficulties presented by failure of the reciprocity law at short flash durations of less than 1-3 msec. have been pointed out (75). Equations are also available for the retinal burn problem (196, 307 ,308 ,431) and planning charts, for flashblindness and retinal burns following nuclear blasts (10).

Retinal Burns

Illumination at the eye of 240,000 lumens/ft^2 represents the probable level required for retinal burns. This is also given as 0.5 to 1.5 cal/cm^2 (118). This energy must be delivered at a rate of at least 0.7 cal/cm^2-sec, however, or the rate of heat dissipation in the tissue will be sufficient to prevent elevation of the temperature to a degree where a burn will result. The threshold appears to depend upon the time of irradiation and upon the size of the irradiated area. See compilation of results available which leads to threshold data as shown in Figure 2-56. The data of Figure 2-55 may be used to arrive at values of J/cm^2 at the retina for external illumination.

Two solutions to the meteoroid or other flash problems are either to prevent the light from reaching the eye or, if this is impossible, to increase the luminance of the instruments after exposure of the eye by flooding them with white lighting (365). Auxiliary storm lights have been used in aircraft for years to combat the relatively mild flash blindness (afterimage formation and loss of dark adaptation) resulting from exposure to lightning flashes. Such lights could probably be used after meteoroid flash as well as after sudden exposure to other sources giving scotomatic glare effects.

Visor materials can attenuate light flashes. When a given filter is placed before the eyes, the change in retinal illumination depends not only on the visual transmittance of the filter but also on the size of the pupil. The size of the pupil, however, varies inversely with retinal illumination. Thus, if the retinal illumination is decreased, the pupil will increase in size and vice versa. Because of this interaction between pupil size and retinal illumination any change in luminance of the visual field will result in a final level of retinal illumination which depends on the change in pupil size as well as the change in luminance. The effective density of a filter is the ratio of the retinal illumination with the filter in front of the eyes to the retinal illumination without the filter. Figure 2-55b indicates that retinal illumination changes only 0.86 log unit for each log unit change in the luminance of visual field behind the filter. It must be remembered, however, that flashes shorter than the pupillary reaction time are attenuated only by the filter factor.

Data on the transmission of light through standard visor materials are available (4 , 82 , 87 , 216). The Class 3, gold-coated visors were designed for eye protection against weapon flashes and are MIL-L38169 (USAF)

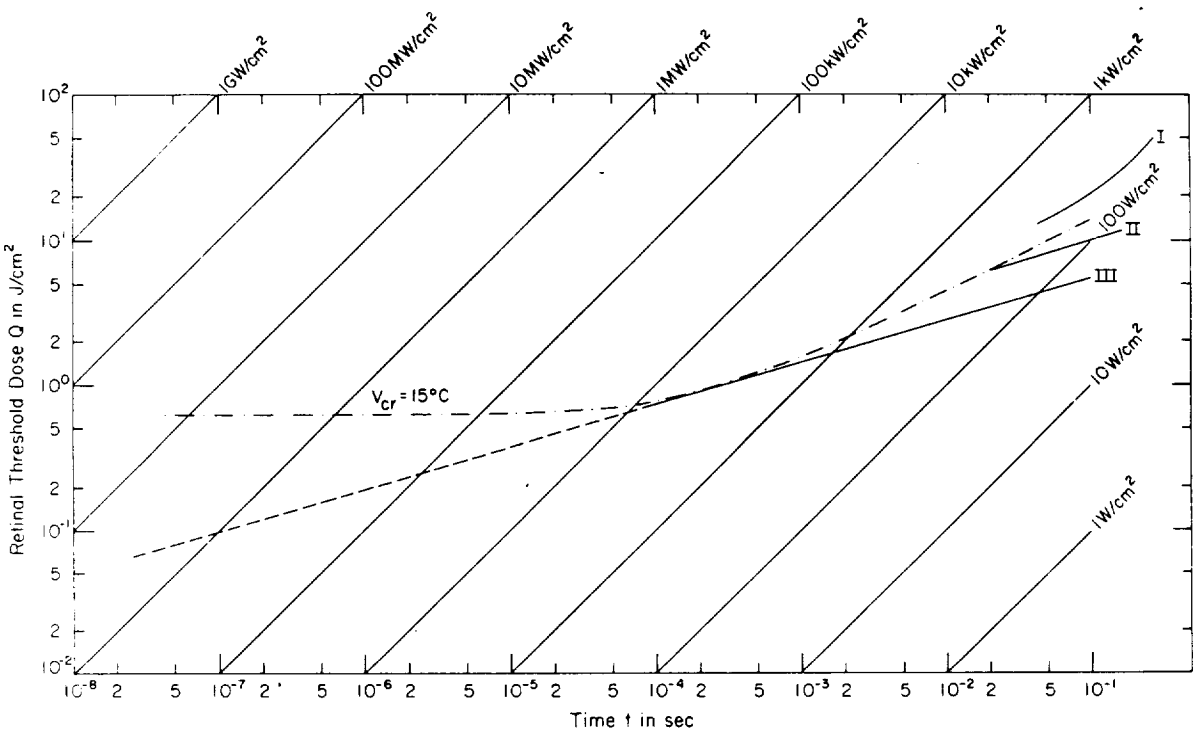


Figure 2-56

The Maximum Dose Q (in J/cm^2) to Produce Retinal Burn, as a Function of Time of Irradiation, with the Irradiated Retinal Area as Parameter. Note that the Threshold Level Is Lower in the Later Experiment Due to Better Diagnostic Techniques. I. Ref.[196] Image Size 240 μ II. Ref.[196] Image Size 700 μ III. Ref.[197] Image Size 1000 μ.

(Adapted by Vos[430] from Data of Ham et al[196, 197])

and MIL-V-22272B (WP). The specified luminous transmittances for these visors are 2 percent ± 0.5 percent and 2.75 percent ± 0.25 percent respectively. The corresponding optical densities are 1.70 plus 0.12, minus 0.10 and 1.56 plus 0.04, minus 0.02 respectively. The relative difference in retinal illumination that the eye would receive from a light flash is 0.86 log units for each unit of density of a fixed filter visor as compared to when no visor is worn. Therefore, the effective densities of the Class 3 visors with nominal densities of 1.70 and 1.56 are 1.46 and 1.34 respectively. (See Section B.Ultraviolet for ultraviolet transmission of these fixed visor systems.)

The use of reversible, variable-density, filter devices to reduce glare and flashblindness in high risk environments has been studied (70, 116, 124, 242, 332). A survey of photochromic materials for potential use in variable filter devices is available (37). The effects of blue-cutoff filters used in photochromic goggles on color discrimination are under study (94).

Laser Burns (Coherent Light)

Design of lasers for navigation and other purposes in space operation brings a new hazard to the skin and eye. Several excellent reviews are available on this subject (196, 197, 221, 249, 267, 268, 279, 315, 338, 430, 464, 465, 466).

All structures of the eye can be damaged, but the retina is the most sensitive structure. Thresholds of retinal damage for different wavelengths are under study and speculation (208, 430 , 431 , 425). Theories of damage span the gap from pure thermal burn (see Figure 2-56) through explosive steam damage, shock waves, Raman and Brillouin scattering, to ionization from intense electric field gradients (208, 342). Failure of the pure thermal model is especially prominent in the giant pulse, Q-switched laser with the actual threshold ten times lower than expected. Here even for minimum image size, the retinal image acts infinitely large (430).

A conservative practice appears to be limitation of total integrated energy into the eye of less than 10^{-8} Joules for pulsed beams (237, 238 , 239). For pulses greater than 30 nanoseconds, an energy factor of 5 times lower should probably be used but no specific recommendations have been made (237, 238). Neither have specific recommendations been made for lasers of shorter wavelength than 633 nm. For purposes of calculations, in the green spectral region, the allowable energy level of 10^{-8}J might be reduced slightly due to the shorter wavelength and increased absorption in the pigment epithelium.

For continuous lasers, the power level in the eye should be kept below 10^{-6} watts.

The BG-18 and A0570 glasses have been recommended for laser protection (237, 238 , 239 , 398 , 430). Standard BG-18 glass is approximately 4.5 mm thick and has an optical density of 10 at 694 nm to 1.3 μ which includes the two most common pulsed lasers. Using the University of California criteria for pulsed lasers, this would appear to be satisfactory for a 100 Joule laser pulse (237, 238). It should be remembered that glass may not retain its integrity with such an exposure. Spalling occurs above 2 cal/cm^2 irradiation densities with a neodymium Q-switched laser; yet even at 8 cal/cm^2, the filter, though cracking, remains to give adequate protection. It has been advised to construct the filter of two cemented halves, so that only the front half cracks under extreme exposure without impairment of its optical safety (398). For this reason, a limit of 20 Joules for the 4.5 mm glass is recommended over the spectral region given above. No direct viewing of pulsed lasers should be allowed regardless of the eye protection used.

At 694 nm the BG-18 glass is increasing its transmission rapidly with decreasing wavelength. It therefore is not applicable for the common HeNe gas laser operating at 633 nm. For continuous lasers the AO-570 glass is used. This glass has an appreciable attenuation at 633 nm with an optical density of about 4.2. Using the University of California criteria this glass would then attenuate sufficiently for lasers of about 30 mW at this wavelength. In actual practice AO 570 glass is recommended for use at power levels up to 100 mW over the spectral region from 633 nm to 1.0 μ . This continuous power is allowed because the critical value of 10^{-6} watt entering the eye contains somewhat more safety factor than is necessary for this portion of the spectrum.

Other approaches have been used for calculating the thickness of BG-18 glass required for protection against different laser types (430). These

equations cover both the near-distance situation where the complete beam enters the pupil and the far-distance situation where magnification of collimating optics and telescopic systems as well as the specular reflection of windows and metal surface must be accounted for. No official U. S. Government Standards have been published, but the issue is currently before the NAS-NRC Committee on Vision.

Skin Effects

The threshold of pulsed laser effects for human skin damage varies with color. White skin of Caucasians has tolerated energy as high as 5-10 Joules without change. At these levels, Negro skin will scale superficially, char, crust, - even ulcerate (175). Above 20-25 Joules in white skin, acanthosis and bizarre nuclei are seen. At about 100 Joules, anesthetic areas and vascular changes are found. Skin burns are covered in greater detail in the Thermal Section, (No. 6).

Environmental Factors in Vision

The acceleration, vibration, oxygen, and nutritional conditions can significantly alter visual performance. The interactions will be covered in the appropriate Sections. (See Sections, No. 7, 8, 10, and 14).

Toxic and Drug Effects on Vision

The most probable toxic material in a spacecraft atmosphere effecting vision is carbon monoxide. Figure 2-57 shows the effect of this gas upon visual light sensitivity. See also Contaminants (No. 13).

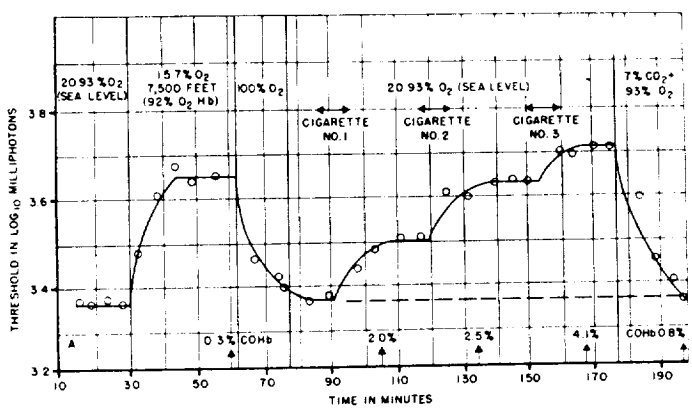


Figure 2-57

The Effect of Smoking on Visual Light Sensitivity as Compared with the Effect of Altitude.
The Effect of Inhaling the Smoke of Three Cigarettes Is Equal to an Altitude of About 8000 Feet.

(After Wulfeck et al[462] Adapted from McFarland[281])

The effects of drugs on the visual system are complex, especially the psychotropic drugs which alter the sensorium at the higher centers. A recent review of this area covers most of the key factors to be involved (14 , 66 , 331, 345, 414,440). Such factors must be considered in the choice of drugs for use in space operations (84).

Visual Performance in Actual Space Flight

There appears to be no severe effect of orbital flight on visual performance. Preflight, inflight and postflight tests of the visual acuity of the members of the Gemini V and Gemini VII crews showed no statistically significant change in their visual capability in zero gravity (131).

Observations of a prepared and monitored pattern of rectangles made at a ground site near Laredo, Texas, confirmed that the visual performance of the astronauts in space was within the statistical range of their respective preflight thresholds. Observations of the Texas ground-pattern site were made under very favorable weather conditions. Heavy clouds blanketed the site throughout the remainder of the mission, however, and no further observations of the site were possible. Successful observations of the ground pattern were made by the command pilot through a clear portion of his window. No direct sunlight fell on the window during those observations. These observations occurred at 27:04:49 and 49:26:48 ground elapsed time (g.e.t.) on the second and third days of the flight, respectively. The circled points represent the apparent contrast and angular size of the largest rectangles in the ground pattern. Apparent contrast was calculated on the basis of measured directional luminances of the white panels and their backgrounds of plowed soil, of atmospheric optical properties measured in the direction of the path, of sight to the point of closest approach, and of a small allowance for contrast loss in the spacecraft window based upon window scan data and readings of the inflight photometer at the time of the two observations. Angular sizes and apparent contrast were both somewhat larger for revolution 31 than for revolution 17 because the slant range was shorter and because the spacecraft passed north of the site, thereby causing the background soil to appear darker. The orientations of those rectangles indicated by double circles were reported correctly, but those represented by single circles were either reported incorrectly or not reported at all. The solid line in Figure 2-58 represents the preflight visual performance of Borman as measured in the vision research van. The dashed lines represent the $-\sigma$, $+\sigma$, and $+2\sigma$ contrast limits of his visual performance. The positions of the plotted points indicate that his visual performance was precisely in accordance with his preflight visual thresholds.

The result of Soviet visual studies in orbit are not much different from those in the U.S.A. (344). Visual acuity of Leonov and Belyayev in Voshkod-2 were measured by hatched mires placed at 300 mm from the eye. Both cosmonauts had visual acuities of 1.7 in the laboratory. In orbit, these decreased to 1.64 for Leonov and to 1.34 for Belyayev. Visual efficiency as measured by reliability was reduced by 20 to 25%; and working time, by more than a factor of 2. The degradation of efficiency was attributed to uncompen-

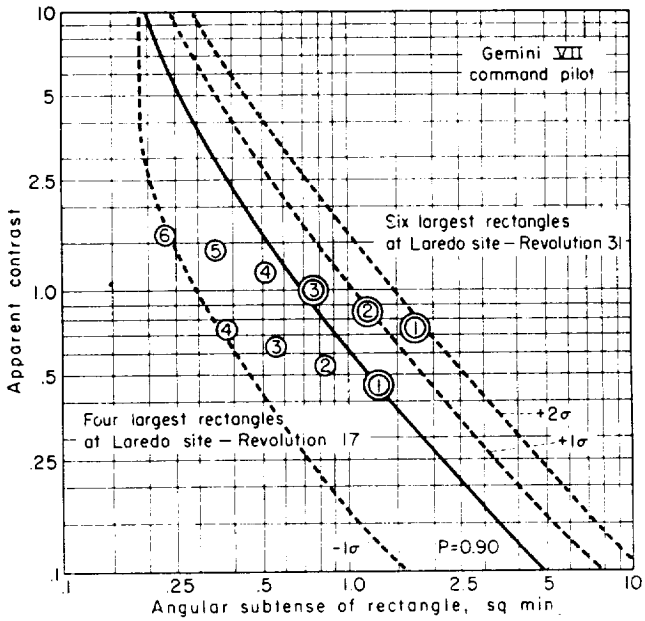


Figure 2-58

Apparent Contrast Compared with Angular Size of Rectangles in Gemini VII. (See text for details.)

(After Duntley et al[131])

sated changes in coordination of occulomotor movement brought about by weightlessness. However, no data are present to support this contention.

Color vision was tested in flight by having the cosmonauts compare the intensity of the colors red, green, blue, light blue, purple, and yellow with the intensity of staggered black and white wedges. The wedges made it possible to measure the intensity of objective colors within an error of 5 to 6 percent for the averaged measurements. By establishing responses for different conditions of color adaptation, simultaneous and consecutive contrast, etc., a mean quadratic error of the monomial equation for the intensity of the colored and black and white fields was obtained. The measurements made at different times with the use of different charts showed that the value of the error for the colors used amounted to ± 7.8%. In Vostok-2, the mean decrease in intensity for all colors tested was 26.1% for Belyayev and 25% for Leonov. The maximum deviations were for purple, light blue and green; and the minimum, for red. The reasons for this change in color perception are not known.

One of the surprises in the manned space flight program has been the ability of astronauts to perceive unexpectedly fine detail on the surface of the earth. L. G. Cooper's visual acuity on the Mercury-Atlas 9 flight was measured as 20/12 on the Snellen scale, versus the conventional 20/20 as "perfect" (121). E. H. White on Gemini 4, also from an altitude somewhat over 100 miles, reported that he too could see roads, boat wakes, strings of street lights, airfield runways and smoke from trains and buildings. Whereas previous estimates for the resolving ability of the human eye, with white-black contrast, were about 1 minute of arc, these observations demonstrated an ability to resolve a half a minute or less (121, 344). These results come in the face of the above suggestions that if any change in visual acuity were to be found in men in space it would be a minor degradation in ability.

The simplest explanation is the fact that many of these targets were of linear shape. The width of lines and bars can be resolved more easily than circles of the same diameter (see discussion of Figures 2-19 to 2-22). One must also include previous experience of the astronauts in detecting landmarks from secondary cues. However, it must be remembered that photographs taken by the astronauts have tended to be more distinct than pictures taken from high-altitude aircraft. Edward White reported that indeed he could see much greater detail on the surface from 100 miles than he could when flying at 40,000 feet. Photographs taken during the Gemini 4 flight, for example, revealed a dark, finger-like streak through the terrain of central Texas that was unknown to geologists despite the fact that the terrain had been surveyed by aerial photographs (85).

A possible explanation of the superior photographs, bearing also on the superior visual acuity, stems from local turbulence in the atmosphere, small nonhomogeneous bubbles in the atmosphere and dust particles in the atmosphere (121). The first two phenomena tend to distort and blur fine image details when they intervene between viewer and target, but the effect will diminish as a function of the distance from the effects since the angle they project relative to the target will diminish. The dust particles can cause back-scattering of light, increasing background luminance and reducing contrast, but again with an effect diminishing with range. These phenomena cannot fully explain an increased human acuity in space, however, because the limit of 1 minute of arc has been derived over the years under laboratory conditions in which, of course, atmospheric effects do not bear on the results. Given an excellent lens, sensitive film and the proper exposure, a camera can see whatever light reaches it, but the eye has an intrinsic threshold both for light energy and contrast beyond which it does not respond. What space flight suggests is that this threshold is lower than had been supposed; remove gravity and possibly the eye can operate more effectively as a sensor, approaching or perhaps reaching its threshold.

Further evidence is provided by a series of zero-g aircraft experiments which found an increase in man's ability to discriminate brightness while weightless, the difference being greatest at the lowest illumination levels (443). By measuring the difference in illumination between the brightness of the target and background required for the subjects to perceive that a difference exists, USAF's Aerospace Medical Research Laboratory found the following improvements in zero g as compared to baseline 1-g measurements:

Illumination (ft-lamberts)	Maximum Difference in Illumination for Detection (%)	
	1 g	0 g
0.03	15.1	12.6
0.28	7.1	6.5
30	4.5	4.0

Since the brief period of weightlessness aboard the aircraft immediately followed a positive g pull-up, it is possible that the eyes of the subjects were sufficiently affected by the increased gravity to bias the results during zero-g before the lens had time to recover.

The effect of zero gravity to improve vision can be two-fold. On the one hand the removal of friction and damping forces on the eye produced by gravity can permit the eye motions to proceed more efficiently in correcting drift. On the other hand, it is possible that part of the explanation for the observed increase in visual acuity lies in part in the effect of weightlessness on the vestibule mechanisms of the inner ear. The effect on the vestibular mechanisms may be such to encourage physiological nystagmus in such a manner as to aid vision by the normal technique of eye motion (143). Electro-oculograms of Soviet cosmonauts have in fact provided evidence that asymmetric oculomotor reactions and nystagmus are different in orbit from those observed on the ground (7 , 254). (See also Acceleration, No. 7.) More work is required on the oculo-vestibular interaction in zero gravity before this hypothesis can be incorporated into the explanation of enhanced visual acuity in space-to-Earth observation.

These findings suggest that laboratory visual acuity data can be combined with environmental optical data to predict correctly man's limiting visual capability to discriminate small objects on the surface of the Earth in daytime under routine orbital conditions. Data are also available on the visual observation of other planets from space (351). A new vision tester for use in future space missions is currently under study (218). Attempts are being made to generate computer programs for prediction of space-to-planet visual capabilities under the many different operational conditions (130).

Data on the observation of stars from Mercury and Gemini spacecraft are covered in the discussion of Figures 2-9 and 2-12 (15 , 445). Little from the reports of the astronauts indicates that the accelerative forces encountered in space flight have had a detrimental effect on vision. The only case of affected vision was reported by Shepard (383). At one point some head vibration was observed. The degradation of vision associated with this vibration was not serious. There was a slight fuzzy appearance of the instrument needles. At T + 1 min 21 sec, he was able to observe and report the cabin pressure without difficulty. The indications of the various needles on their respective meters could be determined accurately at all times. Grissom (184) reported no interference with communication or vision which would seem to confirm Shepard's conclusion that the degradation was due to vibration rather than to acceleration. With respect to the g force experienced during reentry, Shepard reported (383) that reentry and its attendant acceleration pulse of 11 g was not unduly difficult. The functions of observation, motion, and reporting were maintained, and no respiration difficulties were encountered. Glenn noted large oscillations at the end of powered flight but made no note of visual degradation (317).

In the Gemini program, the launch has been free from any objectionable vibration with one exception. On the Gemini V flight, longitudinal oscillations, or POGO, were encountered. The crew indicated that the vibration level was severe enough to interfere with their ability to read the instrument panel. However, POGO lasted only a few seconds and occurred at a non-critical time during this one flight. Unpublished data are available at NASA Ames Laboratory on human response to POGO-like longitudinal vibrations (eyeball in and out) obtained in simulator studies (88). The Saturn boosters appear to have POGO problems.

VISUAL CONSIDERATIONS IN THE DESIGN OF THE SPACECRAFT CABINS AND SPACE SUITS

The preceding data have been presented so as to allow prediction of visual capabilities on the ground and in space. They can be used for specific problems in operational analysis as well as design. The following section covers the general design recommendation for spacecraft illumination, instrumentation and displays considering overall habitability as well as specific operational problems.

General Recommendations for Spacecraft Illumination

Experience in submarines and naval vessels has provided guidelines for optimizing the visual background and decor within the spacecraft. The following suggestions are offered as a result of this and other experiences (5, 48, 152, 271, 301, 389, 412, 419).

In the design of the lighting subsystem, it is necessary to consider those factors which are basic to the provision of artificial illumination most adequate for maintaining comfortable, healthful and effective functioning of normal eyes. These factors are: quality or color of light, intensity of light, and distribution of illumination and brightnesses within the environment. Arrangement of these factors should give compartments a more pleasing appearance and proportions; all three should be combined to induce in the occupants a sense of tranquility, comfort, and "hominess".

The use of color, as a characteristic of a reflecting medium, will be considered in more detail later. Illuminants, however, which vary in spectral characteristics, have an inherent color, which in laboratory situations, at least, affects to some extent the visual acuity. For threshold seeing, spectral yellow, or the yellow light from sodium vapor lamps, is somewhat more effective than other artificial illuminants, although the difference is not of operational significance and does not improve the acuity over that from a similar level of diffused daylight. In ordinary situations (e.g., print reading) the qualities of daylight, mercury arc light, tungsten filament light, and fluorescent lamps are all about equally effective as illuminants, although fluorescent light has been criticized because of its harsh, cold appearance.

The intensity of light has to be considered in relation to: 1) visual acuity; 2) size of object to be discriminated; 3) speed of vision; 4) brightness contrast; and 5) efficiency of performance (48). These have been covered in the previous section. These data suggest that visual acuity increases rapidly up to about 5 foot-candles, and more slowly thereafter, when the object to be discriminated is of about 3-6 minutes of arc. For smaller objects, vision improves perceptibly up to 40 to 50 foot-candles. The greater the brightness contrast, the better is the visual efficiency, and both acuity and speed of vision continue to improve slightly up to and beyond 100 foot-candles. However, little is gained in acuity by increasing the illumination beyond 25 foot-candles, and there is no practical gain at all when the intensity is higher than 50 foot-candles. For large objects,

subtending four minutes of arc and above, there is no practical improvement in visual discrimination with illumination above 20 foot-candles. For smaller objects, there is improved visual discrimination at higher levels up to a limit of about 40-50 foot-candles.

The data on speed of vision may be summarized as follows: a) for objects subtending three minutes of arc or larger, and with good contrast between object and background, speed of vision is near maximum at about 15-20 foot-candles; b) for small objects on a background of low reflectance significant decreases in time for seeing occur with illumination intensities up to about 50 foot-candles.

With respect to brightness contrast, when the contrast between object and background is high, discrimination of arc sizes of three to six minutes is not significantly improved by illumination above 20 foot-candles. With an object of 1-minute size, performance improves significantly up to a practical limit of about 50-60 foot-candles. The greater the brightness contrast, the better is the visual discrimination, although, as will be noted in the examination of light distribution, the effort of seeing is more fatiguing with high contrast. Excessive illumination will not compensate for small object size or poor contrast.

Brightness contrast is also of significance in consideration of distribution of illumination, and in this connection it must be distinguished from glare. The effects of glare can be minimized by increasing the brightness contrast between the object and its immediate background, and by increasing the illumination on the visual object. Elimination of the glare source, however, by removal, or by use of diffuse or indirect lighting, is superior. For best overall vision, with minimum fatigue, the brightness ratio between the central field and surround should not exceed three or five to one; ratios of ten to one should be avoided (Figure 2-45). The extent to which excessive brightness contrast is diminished is largely determined by the degree to which the lighting is indirect, that is, reflected from all directions. When light is properly diffused there are no shadows, no dark corners, and no areas of relatively high brightness. Light fixtures in the field of vision should have a surface brightness of not over 2 candles per square inch and preferably less (412). Thus, vision is generally best when the surround is at the same brightness as the central field unless the visual object approaches the thresholds of acuity or discrimination, in which case, supplementary lighting can be utilized to increase the brightness ratio, provided the latter does not exceed three or perhaps five to one (271). Intensity and distribution, however, must be coordinated. To increase intensity without distribution will only make a bad situation worse. In fact, when distribution is poor, relatively low intensities must be employed to avoid visual discomfort.

In relation to illumination, color serves two purposes in the perceived environment. It determines the reflectance of colored objects in that environment, and it has a psychosocial influence on the emotional set of individuals in that environment. From the point of view of visual perception, the reflection factor of walls, ceilings, and furnishings of any living or working space is more important than the color used, since the reflecting

surfaces become, in effect, secondary sources of illumination. The reflectance of a surface is the ratio of the light flux reflected from the surface to that striking the surface. Dependent upon the surface, it may be diffuse, specular, or compound. Diffuse reflectance arises from a matte surface; specular reflection comes from a highly polished (mirror) surface and gives rise to glare. A compound surface has qualities of both. The color of an object arises out of selective reflectance and absorption of particular wavelengths of the incident light. For any specified level of illumination a region with highly reflecting surfaces requires a less intense light source than one with low reflecting surfaces. Table 2-59 indicates the reflectance factors for various surface finishes.

Table 2-59

General Reflectance Factors for Various Surface Finishes

Color	Percent of Reflected Light	Color	Percent of Reflected Light
White	85		
Light		Dark	
cream	75	gray	30
gray	75	red	13
yellow	75	brown	10
buff	70	blue	8
green	65	green	7
blue	55		
Medium		Wood finish	
yellow	65	maple	42
buff	63	satinwood	34
gray	55	English Oak	17
green	52	walnut	16
blue	35	mahogany	12

(After AFSCM 80-3[5])

Recommended workplace reflectances for different areas include the following: console panel 20-40%; instruments 80-100%; floors 15-30%; walls 40-60%; ceilings (i.e., above eye level) 60-95% (5).

For decorative purposes, contrast is desirable. Lack of contrast variation tends to be monotonous and undesirable. Good decorative schemes cannot readily be achieved with a one to one ratio. The blending of highlights and shadows adds attractiveness to the living space, and can be better achieved with higher ratios, while still remaining within acceptable limits. It should be recommended, however, that the unique characteristics of space system stations, such as restricted internal volume, irregular compartment configurations, multipurpose regional usage, compact working consoles, and special power supplies, may make application of conventional illumination standards inappropriate.

General recommendations for instrument, cockpit and console lighting for aircraft are consolidated in Table 2-60 and should be applicable to work areas of spacecraft. An extensive review of illumination recommendations for specific visual tasks is available (183). Charts, tables and calculation sheets have been prepared to aid the designer in rapidly calculating lighting distribution and average illumination conditions in symmetrical rooms (324).

Table 2-60

Instrument, Cockpit, and Console Lighting

CONDITION OF USE	RECOMMENDED SYSTEM	BRIGHTNESS OF MARKINGS	BRIGHTNESS ADJUSTMENT
Instrument lighting, dark adaptation critical	Red flood, indirect, or both with operator choice	.02 to 0.1 ft.L	Continuous thru range
Instrument lighting, dark adaptation not critical	Red flood or low color temperature white, indirect or both with operator choice	.02 to 1.0 ft.L	Continuous thru range
Instrument lighting, no dark adaptation required	White flood	1 to 20 ft.L	May be fixed
Control console lighting, dark adaptation required	Red edge lighting, additional red flood lighting desirable.	.02 to 1.0 ft.L	Continuous thru range
Control console lighting, dark adaptation not required	White flood	1 to 20 ft.L	May be fixed
Possible exposure to bright flashes	White flood	10 to 20 ft.L	Fixed
Simulated instrument flying (blue amber)	White flood	10 to 20 ft.L	Fixed
Very high altitude, daylight restricted by cockpit design	White flood	10 to 20 ft.L	Fixed
Chart reading, dark adaptation required	Flood, operator's choice of red or white	0.1 to 1.0 ft.L on white portions of chart	Continuous thru range
Chart reading, dark adaptation not required	White flood	5 ft.L or above	May be fixed

(After Baker and Grether[25])

Role of Color in Habitability (152)

The psychosocial aspects of color have received much study (40, 41, 42, 327). Color is perceived within the context of texture and setting. Sometimes it is identified with a surface, sometime with a volume, a film, an illumination, or illuminant. The perception of color is determined by the factors outlined in Figures 2-28 to 2-31 but is influenced by the mental set. It is more than the mere consciousness of color, or even consciousness of modes of appearance of color, but is influenced by the connotations of the color and its associations in the light of past experience. Distinctive color preferences exist. Studies of numerous investigators show the following order of preference of six common colors among over 20,000 observers: blue, red, green, violet, orange, yellow (142).

Although dominant wavelength, or hue, is significant in the determination of color preference, luminance (or reflectance), and purity, are also important. The appeal of a color increases with increasing luminance until

the comfort limit is exceeded, following which there is an increasingly violent loss of appeal. Somewhat similarly, appeal increases with increase in purity up to the spectrum limit in many individuals, although a substantial minority favor weak unsaturated colors (327). The increase in affective value noted in these circumstances is in relation to tests with very small areas of color; it is probable that when areas are large, as in compartment walls, these factors do not apply. The size of the colored area, saturation or tint, hue or shade, and harmony of color patterns tend to combine to give specific emotional responses (152, 327 ,412).

Thus, color should provide both reflecting surfaces and pleasing combinations. Saturated colors and color of low reflectance should be avoided on large areas; tints of appropriate color should be used instead. A proper proportion of reflectance should be maintained on consoles, panels, instruments, floors, ceilings, and walls. Variety in color of decoration is desirable. To maintain a pleasing environment, with appealing contrasts, different colors should be used in the same compartment, and still different combinations in other compartments. Tints and light grays possess several advantages; they make a compartment appear more spacious and ceilings appear higher. Some of the favored colored tints are buff with umber, ivory, cream, blue, coral, and peach. Flat or matte-surface paints should be used to avoid specular reflection. A light that enhances warmth and softness of colored objects is desirable, and furthermore illumination should be such that it does not markedly alter the color of natural objects, e.g., skin complexion and food.

Within these limitations, a variety of colors can be selected for the interior of spacecraft and space dwellings. Cool, work-stimulating colors are recommended for the work area, with bright contrasting accents on trim; warm, relaxing colors are recommended for public rest and recreation areas, again with contrasting accents and trim; while subdued, "homey" colors will be appropriate for personal areas. General lightening of color values will assist in providing brighter interiors with a lower level of illumination. The latter, as much as feasible, should be indirect, diffuse and non-glaring.

The following recommendations have been suggested for the illumination system of spacecraft (152, 418):

(1) White light illumination be provided for most mission phases.

(2) The intensity be variable from 0.1 m-L to about 40 m-L with the highest intensity for launch and flashblindness emergencies.

(3) An intensity of 10 m-L be provided as the maximum value for non-launch conditions with local illuminance levels recommended above.

(4) Provisions be made for turning off all internal lights with critical instruments being self-illuminated (according to Table 2-60) and for maintaining interior/exterior light balance.

(5) Flexible floodlights should be provided to reduce extreme contrast to less than 5:1 between target area and general surround.

(6) The reflectivity of suits, equipment, and interior paints be used to increase the evenness and diffuseness of lighting.

(7) Color of interior should be pleasing, of low saturation and appropriate reflectance, and of warm and restful quality in public and personal areas.

(8) Red filters (6400 Å) be provided for dark adaptation for all light sources, and the color of critical markings and legends be designed so that they can be seen when red lighting is used.

(9) Trans-illuminated displays should be used and shielded to prevent their being masked by high-intensity light sources. (389) For night operation, the average cockpit display luminance should be minimized.

(10) Lights, indicators, and self-illuminated instruments be located to prevent reflections from windows and other instruments.

(11) Filters, or shutters be provided for the windows to reduce undesirable illumination.

(12) Filters or shutters be readily operable to aid the astronaut in programming light to achieve optimal light levels.

(13) The color and intensity of caution and warning lights be considered, as they influence ambient illumination levels and dark adaptation, particularly for the dark side of the Earth (389).

(14) Inadvertent light leaks, particularly from high-intensity sources, be identified and corrected before the mission for each spacecraft, to ensure that low levels of interior illumination and dark adaptation can be maintained.

Viewing Ports and Visors

The viewing ports of spacecraft often require extreme accuracy for sighting and resolution, especially where optical experiments are being performed. The efficiency of the visual system is a function of the clarity of the optical window, lighting, and the angles between line of sight and window. The data of Figure 2-61 were obtained from subjects who looked through aircraft glass, clean plexiglas, and dirty plexiglas. Deterioration of optical properties of glass in Mercury and Gemini capsules by exhaust from the escape tower and by deposition of sublimated gasket material has been reported (409).

A review of windows for aerial photography is available (150) as are data on optical characteristics of a Gemini window (436).

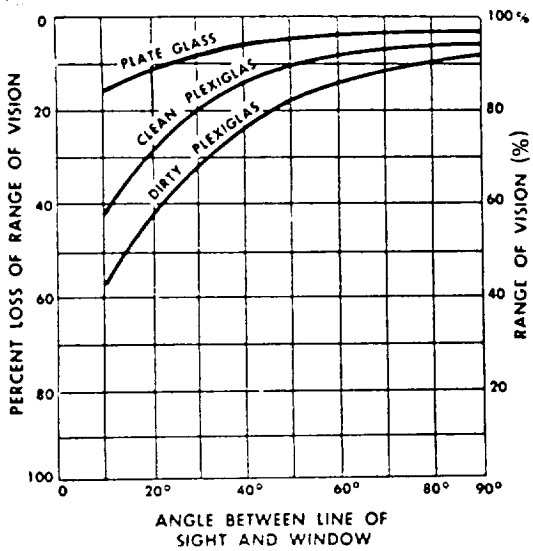


Figure 2-61

Clearness of View

(After Olenski and Gooden[326])

There are several visual problems caused by helmets and visors:

1. Field restrictions.
   Helmets should permit the widest possible visual field. Visors with the largest possible area should be used and visual fields determined with and without head movement.

In the Apollo helmet and visor system (423) it has been suggested that the crewman be able to see downward to a point on the front torso center-line 6 inches below the neck ring. With the crewman standing and nodding in an erect PGA, he should be able to see the toes of the boots. When the crewman is subjected to a sustained acceleration of 10 g's eyeballs in, enclosed by a pressurized suit, and secured to the command module couch, vertical field of vision should not be reduced by fault of the helmet upward or downward.

The recommended unrestricted range of vision is as follows:

a) Horizontal Plane: 120° left, 120° right.

b) Vertical Plane: 105° down, 90° up.

Minimum vision requirements in a compound direction (example: upper left-hand corner) are defined by an ellipse through the specified vertical and horizontal points. With the head moved forward, eye relief for the primary pressure retention visor is 2.06 inches. This eye relief applies over a vertical range from 45° up to 10° down.

2. Optical distortions.
   Optical distortions can be produced by curvature of visors, point-to-point differences in thickness, prism errors, changes in head position, non-neutrality, etc. No visible distortion or optical defects detectable by the "unaided eye" at the typical "as worn" position should be visible. The definition of "unaided eye" is a person who has a visual acuity of 20/20 or better.

For the Apollo visor system it has been recommended (423) that the refractive power in any meridian not exceed by more than plus or minus 0.06 diopters the power inherent in a spherical lens with concentric surfaces having the proper radii of curvature and thickness. The inherent power of the visor is calculated by use of the following formulae:

$$F = F_1 + F_2 - \frac{t}{n}; \quad F_1 = \frac{n' - n}{r_1}; \quad F_2 = \frac{n - n'}{r_2} \qquad (11)$$

where F = Power of the lens in diopters

F_1 = Power of the convex surface in diopters

F_2 = Power of the concave surface in diopters

n = Index of refraction of air

n' = Index of refraction of the material

r_1 = Radius of first or convex surface

r_2 = Radius of second or concave surface

t = Thickness in meters

Prismatic deviation includes the inherent prismatic power resulting from non-parallel surfaces of the material. The vertical prismatic deviation between the right eye and the left eye should not be more than 0.18 diopters at any point in the area of vision. The vertical prism at any point in the area should not exceed 0.18 diopters at either eye.

The horizontal prismatic deviation is stated for specific regions of the typical visor given in Figure 3.1-7 of Ref. 423. The algebraic sum of the horizontal prismatic deviation at point "C" for the left eye and at point "C" for the right eye should not exceed 0.75 diopters. The algebraic difference between the horizontal deviation at point "C" for the left eye and at point "C" for the right eye should not exceed 0.18 diopters.

3. Optical transmission.
The transmission of light through the visor should be controlled to minimize the effects of glare and flashblindness, ultraviolet damage to the cornea, infrared heating, and haze. The light transmission and optical characteristics of plastic visors used in military helmets for aircrew are available (4, 82, 87, 216).

For the Apollo system it has been recommended that the luminous transmittance of the pressure-retention, primary visor should not be less than 80 percent throughout the critical areas of vision noted in Figure 3.1-7 of Ref. 423. Other visor areas should not vary in transmittance by more than ± 5% of the critical area transmittance. The total luminous transmittance through all visors including the antiglare supplemental visors, is a maximum of 10%. The transmittance for the left and right eyes do not differ by more than 5%. The haze value of the visor should not exceed 5%.

The spectral transmittance of the pressure visor may vary with wave lengths between 380 and 770 nm, the average percentage deviation within nine spectral bands should be less than 12. (See Figure 3.1-7 of Ref. 423 for sample calculations.)

For control of electromagnetic transmittance in the visor system, the following has been recommended: (423)

a) Ultraviolet - The transmission of ultraviolet radiation in the range 220-320 nm be such that the total energy incident on the cornea and facial skin shall not exceed 1.0×10^5 ergs cm^{-2} in any 24 hours period. (See Ultraviolet light, Section 2, part B.)

b) Infrared Transmittance - The transmittance of infrared radiation beyond 770 nm not exceed a total value of 10 percent with all visors in place.

c) Visible - The primary visor have a transmittance in the visible range of at least 85%. The maximum transmittance through the primary visor and the least dense sector of one secondary visor should be 60%. The maximum transmittance utilizing all visors should be 2%.

The temperature of the facial skin can also be used as a limit in the design of the visor system. It is recommended that in sunlight, the facial skin temperature should not exceed 100°F.

It has also been recommended that the chromaticity coordinates of the anti-glare visor be within the limits indicated in Fig. 3.1-8 of Reference 423 when computed by the techniques of Reference 2-1.

4. Visual impairment due to fogging.
Fogging of visors due to a combination of high humidity in the helmet and low temperature of the visor surface must be prevented. Serious degradation of performance can result from this design problem. Anti-fog coatings or heating can be used to allow fog-free conditions under zero air flow and 100% humidity. About 33 watts/in^2 of thermal input may be required for thermal control of fogging (355).

Instrumentation and Displays

The visual factors in the design of instruments and displays have been summarized by several good reviews (25, 148, 280, 304, 457). The following discussion represents only the more generalized visual aspects of the problem. The original reviews should be consulted for specific design details when required.

Telescopic Devices

Manned star tracking in navigation has received much study (11, 149, 320, 321). It has been shown that man can track to a 1 sigma accuracy of 0.05 milliradians in elevation and 0.12 milliradians in azimuth using a manually slewed, eight-power telescope. A 1 sigma tracking error of 0.01 mill is possible using a 28 power rate control telescope. The minimum field of view required for tracking has also been studied (11). Results indicate that star recognition time varies significantly as an inverse function of field of view size; star recognition times for viewing fields of 10, 15, and 20 degrees are significantly greater than for viewing fields of 30, 35, 40, and 45 degrees; star recognition performance does not appreciably change for viewing fields greater than 25 degrees; the majority of star identification errors (81 percent) occurs for viewing fields of 25 degrees or less; the time required to recognize stars, up to some maximum proficiency level is significantly related to the amount of training the knowledge of the star constellation. Data on effects of magnification and observation time on telescopic target identification in simulated orbital reconnaissance are available (386).

Dials and Scales

In the design of dials and scales, the scale base-length reading distance, number of scale divisions, and scale interval are key variables (311). Figure 2-62a is a nomograph showing this relationship.

Alteration of scale units for low cockpit luminance conditions has been studied (445). At the viewing distance of 28 inches and minimum night lighting of 0.01 to 0.002 ft lamberts, the graduation interval should not fall below 0.11 inches and the width of minor graduation marks should be approximately 0.032 inches for optimum speed and accuracy of reading. The following scale numbering and graduation interval values have been recommended in the Apollo system (423): (1) Scale graduations progress by 1, 2, or 5 units or a decimal multiplier of those numbers; (2) The number of minor graduations between major markings does not exceed nine; (3) An increase in numerical progression reads from left to right or bottom to top; (4) Major graduation marks are whole numbers; and (5) Maximum contrast between scale face and markings is maintained, i.e., black scale markings against white background.

For rapid and accurate readings under illumination conditions as low as 0.003 foot lamberts, the dimensions in Figure 2-62b are recommended. This figure is based on a 28-inch viewing distance. For other distances, multiply these dimensions by the factor:

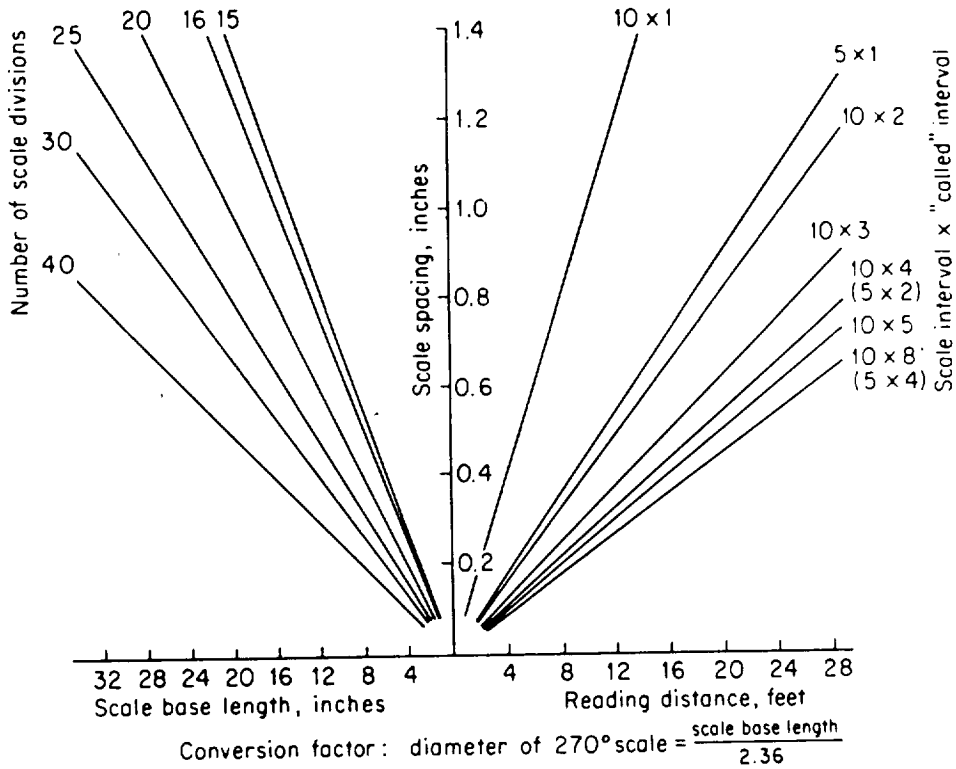
$$\frac{\text{Viewing Distance in Inches}}{28} = \text{Graduation Mark Dimension and Spacing} \qquad (12)$$

When illumination levels exceed 1 to 2 foot lamberts and where reading time is not critical, smaller graduation marks of the same general proportions may be used and the separation between marks can be reduced to a minimum of 0.35 inches.

Figure 2-62

Dial and Scale Design

a. Dial and Scale Design Nomograph.



Nomograph showing relationship between reading distance, scale interval, "called" interval, and scale base length. The method of using the nomograph to find the dial size when the maximum reading distance is known can be illustrated by a 200-lb pressure gauge subdivided into 20 scale divisions at 10-lb intervals, to be read at a distance of 20 ft, to a "called" interval of 2 (the smallest value to be read). Enter the right side of the nomograph at 20 ft and more vertically until the 10 x 2 line is cut (10 x 2 is the scale interval, 10 multiplied by the "called" interval, 2 lb). From this 10 x 2 line horizontally to the 20 line (there being 20 marked scale divisions) and down to the base line to give a scale base length of 17½ in.; to obtain the diameter, divide by 2.36 to give 7.4 in. In practice this means using a standard gauge with an 8-in. dial blank. The nearness of scale base length of 17½ in. at 20-ft reading distance to a 1:1 ratio has led the British Standard Institution to suggest the use of a scale base length of 1 in. for each 1-ft reading distance as a useful working relationship. To obtain the maximum reading distance when the dial size is known, the procedure described above is reversed. It may be noted that should the 200-lb gauge be subdivided into 40 scale divisions, giving a 5 x 2 interpolation, the scale diameter will be 9.1 instead of 7.4 in. In fact, any method of a subdivision other than 10 x 2 gives a less favorable result, which suggests that for industrial scales, subdivision into 20 parts and interpolation into 5ths is optimum.

(After McCormick[280] Adapted from Murrell, Laurie, and McCarthy[311])

Figure 2-62 (continued)

b. Minimum Recommended Circular Scale Diameters Under Illuminating Conditions as Low as 0.003 ft Lamberts in Apollo.

After NASA CSD-A-096 (423)

Number of Graduation Marks	Viewing Distance		
	20	28	36
	Diameter of Circular Scales		
35			1.00
45		1.00	1.23
50		1.11	1.43
63	1.00	1.40	1.80
100	1.59	2.23	2.87
150	2.39	3.35	4.30
200	3.18	4.45	5.73
250	3.98	5.57	7.77
300	4.77	6.68	8.60
350	5.57	7.80	10.00

The number of graduation marks required on a circular scale imposes a limit on the minimum diameter of the scale. The minimum distance between graduation marks viewed from a distance of 28 inches is 0.07 inches. For other viewing distances, Figure 2-62b shows recommended minimal diameters for three viewing distances and various numbers of graduation marks.

Letter location on scales and dials has been recommended as follows (423): On circular stationary scales, orient all numbers to be read horizontally instead of medially. On moving scales, orient all numbers to be upright at the reading position.

The general design requirements for moving-pointer, fixed-scale type indicators (circular) are presented for the Apollo system (423). Clockwise movement of the pointer should result from (1) clockwise movement of an associated rotary control, or (2) movement forward, upward, or to the right of an associated lever or switch, vehicle or component. In cases where positive and negative values around a zero value are being displayed, the zero should be located preferably at the 12 o' clock position although the 9 o'clock position is also acceptable. The positive values should increase with clockwise movement of the pointer and the negative values increase with counter-clockwise movement. Except on multi-revolution instruments such as the clock, there should be an obvious scale break between the two ends of the scale of not less than 1-1/2 divisions. The numerals are usually placed inside of the graduation marks to avoid constriction of the scale. If space is not limited, the numbers may be placed outside of the marks to avoid having the numbers covered by the pointer.

In the design of moving-pointer, fixed-scale type indicators (linear and curved, or arc scales), pointer movements are recommended as above (423). In cases where positive and negative values around a zero value are being displayed, the positive values should increase with movement of the pointer

up to the right and the negative values increase with movement of the pointer down or to the left. Movement of the pointer up or to the right should result from (1) clockwise movement of an associated rotary control, or (2) movement upward, forward, or to the right of an associated lever or switch. Numerals should be placed on the side of the graduation marks away from the pointer to avoid having the numbers covered by the pointer. For curved or arc scales, the numerals will be placed inside of the graduation marks to avoid constriction of the scale. If space is not limited, the numbers may be placed outside of the marks to avoid having the numbers covered by the pointer. The pointer is located to the right of vertical scales and at the bottom of horizontal scales.

Fixed-pointer, moving-scale indicators are not recommended for general use (423). If, however, the situation dictates their use, the progression of numbers and response to control should follow those recommended for moving-pointer systems. The numbers on the indicator should progress in magnitude in a clockwise direction around the dial face. In case of vertical or horizontal moving straight scales, numbers should increase from bottom to top or from left to right. If the associated control has a direct effect on the behavior of the vehicle, the scale should rotate counter-clockwise with (1) clockwise movement of the associated knob, wheel, or crank; (2) movement forward, upward, or to the right of a lever; or (3) movement forward, upward, or to the right of the vehicle or component. However, if the associated control has no direct effect on the behavior of the vehicle, the scale should rotate counter-clockwise with counter-clockwise movement of the associated knob or crank. The pointer of lubber line position should be at 12 o'clock for right-left directional information and at 9 o'clock for up-down information. For purely quantitative information, either position may be used. If the display is used for setting, such as tuning in a desired wavelength, it is usually advisable to cover the unused portion of the dial face. The open window should be large enough to permit at least one numbered graduation to appear at each side of any setting.

The desirable size of numerals and letters is affected by the distance at which they are to be read. For the usual reading distance of about 28 in., it has been reported that two different sizes of block capital letters seem to satisfy the concurrent desirability for uniform size with occasional larger letters for emphasis (74). These two sizes are 9/64 in. for the bulk of the letters and 11/64 in size for emphasis. Illumination, reading conditions, distance, and the importance of accuracy should of course be taken into account in selecting the size of letters or numerals for use as labels or markings (280, 304).

A formula has been developed that takes into account illumination, reading conditions, viewing distance, and the importance of reading accuracy (280, 340):

$$H \text{ (height of letter in inches)} = 0.0022\ D + K_1 + K_2 \qquad (13)$$

where D = viewing distance

K_1 = correction factor for illumination and viewing condition

K_2 = correction for importance (for important items such as emergency labels, K_2 = 0.075; for all other conditions, K_2 = 0.0).

This formula has been applied to various viewing distances, in combination with the other variables, and the heights of letters and n' merals derived therefrom. These values are given in Table 2-63. It should be kept in mind that these are approximations of desirable heights; values within reason of those given would generally produce relatively comparable legibility. Needless to say, one should not apply such a formula arbitrarily, without taking into account special facets of the particular situation. A set of recommended heights for the Apollo System at 28" viewing distance, low brightness (down to 0.03 ft L) range from 0.05 to 0.20 in. for noncritical, normal situations, up to a range of 0.20 to 0.30 in. for critical, adverse situations (304, 423).

Table 2-63

Table of Heights of Letters and Numerals (H) Recommended for Labels and Markings on Panels, for Varying Distances and Conditions Derived from Formula H (in.) = 0.0022 D + K_1 + K_2

(After McCormick[280] Adapted from Peters and Adams[339])

Viewing distance, inches	*0.0022 D value*	*Nonimportant markings*			*Important markings*		
		K_1 = 0.06	K_1 = 0.16	K_1 = 0.26	K_1 = 0.06	K_1 = 0.16	K_1 = 0.26
14	0.0308	0.09	0.19	0.29	0.17	0.27	0.37
28	0.0616	0.12	0.22	0.32	0.20	0.30	0.40
42	0.0926	0.15	0.25	0.35	0.23	0.33	0.43
56	0.1232	0.18	0.28	0.38	0.25	0.35	0.45

Illumination level, fc	*Reading situation*	K_1 *value*
Above 1.0	Favorable	0.06
Above 1.0	Unfavorable	0.16
Below 1.0	Favorable	0.16
Below 1.0	Unfavorable	0.26

In a study relating to legibility of numerals at distances of several feet, a relationship between height of numerals and legibility was established as shown in Figure 2-64. Each of the three areas indicates, generally, the relative legibility of numerals seen under reasonably normal viewing conditions for persons with normal vision.

The use of color contrast to improve alpha numeric legibility has received recent review (283). The recommended use of color in the design of indicator warning lights is shown in Table 2-32c.

Both for maintaining dark adaptation and avoiding objectionable reflections, it is necessary to use the minimum instrument illumination which will

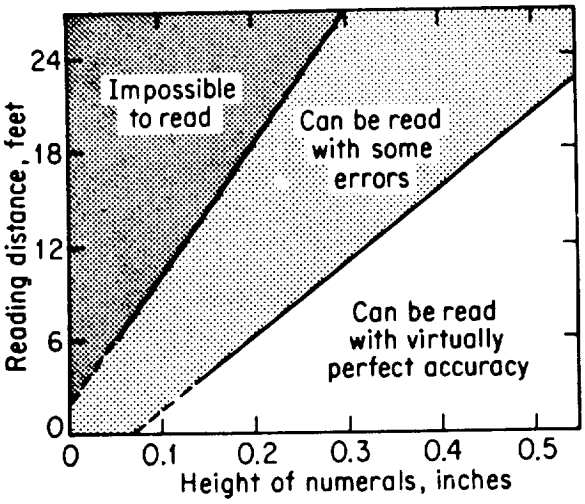


Figure 2-64

Figure Showing Relationship Between Height of Numerals and Legibility of Numerals at Various Distances. The Indications of Degrees of Legibility of Those Height-Distance Relationships in the Three Areas are Generally Valid for Persons with Reasonably Normal Vision.

(After McCormick[280] Adapted from Murrell, Laurie, and McCarthy[311])

permit adequate instrument reading. Figure 2-65 shows the relationship between the brightness of instrument markings and relative efficiency of instrument reading.

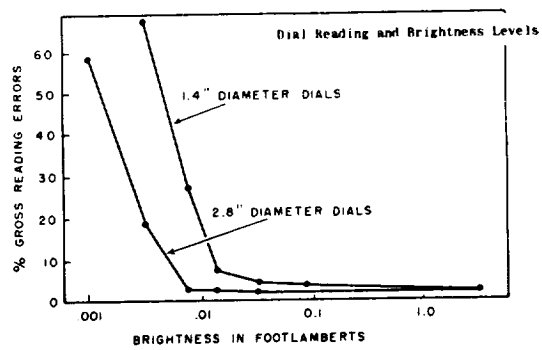


Figure 2-65

Dial Reading and Brightness Levels

(After Baker and Grether[25] from Data of Chalmers et al[90])

In the design of counter systems it is recommended that numbers change by snap action in preference to continuous movement (423). Space between numerals should be no more than 1/2 the numeral width. The height to width ratio of numerals for counter displays should be 1:1 rather than 5:3 as recommended for dials and scales. Numbers should not follow each other faster than about 2 per second if the observer is expected to read the numbers consecutively. Counters used to indicate sequencing of equipment should be designed to reset automatically upon completion of the sequence. Manual provision for resetting is usually provided. The rotation of the counter reset knob is conventionally clockwise to increase the counter indication or to reset the counter. Counters are mounted as close to the panel surface as possible to maximize viewing angle and minimize parallax and shadows.

CRT (Cathode Ray Tubes) Displays

In the design of radar and other displays of the CRT type, the minimum size, shape, and brightness contrast of target on scope is a key factor as is duration of presentation (160, 457, 462). Figure 2-66 shows the relation of a target size to accuracy and relative speed of identification of display targets of this latter type. From the curve, it is evident that, when the visual angle subtended by the largest dimension of the target is smaller than 12 min, there is an increase in relative search-to-identification time and an

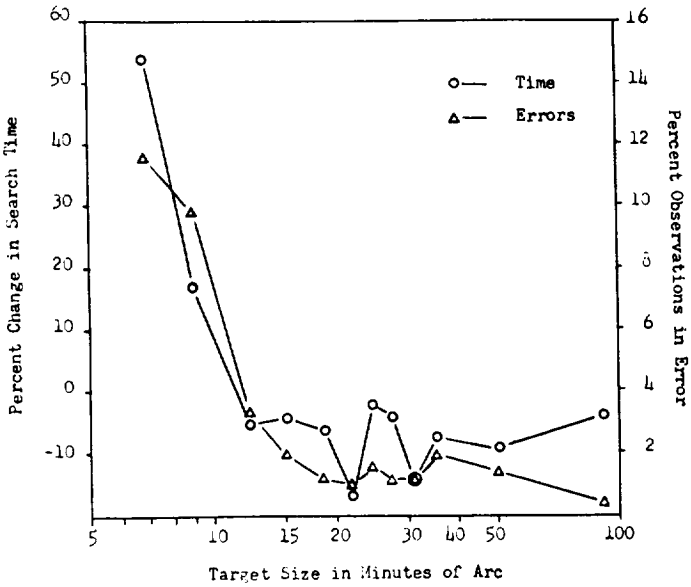


Figure 2-66

Effect of Target Size on Identification Time in Search on CRT Scopes.

(After Steedman and Baker[396])

increase in the number of errors in identification. These and other research data indicate that it probably is safe to assume that targets should subtend, as a minimum, 12 min of arc to insure reasonably accurate identification (457).

Dark adaptation can affect detection on CRT (cathode ray tube) displays. The visibility of threshold targets is best when the operator is visually adapted to the level of the scope brightness. The time lost in the detection of a target on a CRT scope as a function of the pre-exposure brightness for various scope brightnesses is shown in Figure 2-67 (199). The signal, which subtended a visual angle of 20 min of arc at the eye has a 99% probability of detection for an operator whose eyes were adapted to the brightness level of the task. In this experiment, a detection time of 5 sec is equivalent to immediate detection because it took that long for the subjects to move from the adaptation screen to the CRT scope.

It can be concluded that (304):

- For very dim scopes (0.0001-mL background brightness) the operator can be pre-exposed to brightnesses as high as 0.01 mL without impairing target visibility.
- For dim scopes (0.022-mL background brightness) the operator can be pre-exposed to brightnesses as high as 2 mL without impairing target visibility.
- For moderately bright scopes (0.22-mL background brightnesses) the operator can be pre-exposed to brightnesses as high as 20 mL without impairing target visibility.
- A completely dark-adapted operator will suffer a slight loss in detecting threshold targets on scopes with background brightnesses of about 0.02 mL and above.

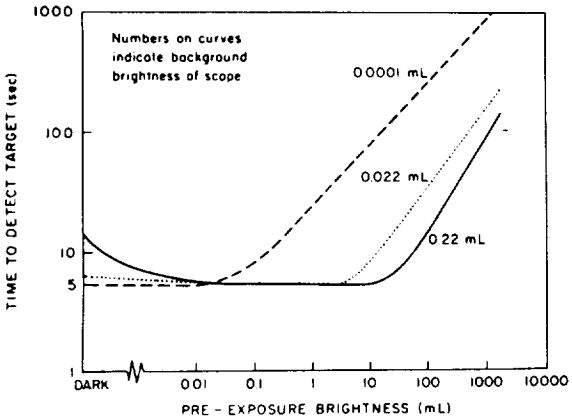


Figure 2-67

Effect of Pre-exposure Brightness on Time to Detect Target on CRT Scopes of Different Brightness Values.

(After Hanes and Williams[199])

If the operator must do other visual tasks at higher brightness levels than those required for the above, visibility will not be seriously affected if the higher brightnesses are not more than 100 times as bright as the average brightness of the radar scope. In other words, if the operator must scan daylight skies (about 2,000 mL), the average scope brightness should be set up to 20 mL or more to maximize visibility under these circumstances (280, 462).

The intensity contrast of the target on a scope is also a factor for CRT displays (199, 217, 457, 462). The curves in Figure 2-68 show the time required for a target to be detected as a function of the pre-exposure brightness for targets of various intensities. In every case, the scope background brightness is 0.022 mL, and the target subtends a visual angle of 20 min of arc. As before, the detection time of 5 sec represents immediate detection. The lowest contrast (13%) is for a target having about 99% probability of detection for operators adapted to the brightness level of the task. The other targets are above this threshold level.

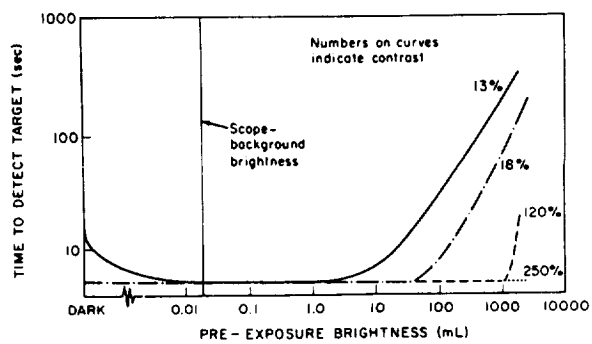


Figure 2-68

Effect of Intensity Contrast and Pre-exposure Brightness on Target Detection of CRT Scopes.

(After Hanes and Williams[199])

It is evident that, with stronger signals (higher contrasts) the range of tolerable adapting brightnesses is much greater. Indeed, for this background brightness (0.022 mL), a target that is 2 1/2 times as bright as the background can be seen immediately after the operator has adapted to 2,000 mL. Thus, if a given radar operation does not require the detection of weak signals, greater tolerances in the operator's brightness adaptation are permissible.

After the eye has been exposed to relatively high brightnesses for about 2.5 min, it reaches, for all practical purposes, a "steady state" of adaptation. This means that longer periods of pre-exposure have little further effect on

the immediate sensitivity of the eye. If shorter periods of pre-exposure are used, however, the sensitivity is affected proportionately less. This relationship is shown in Figure 2-69, in which, for any given exposure duration, the value on the ordinate is used as a multiplier of the exposure brightness to give the steady-state-adaptation level of the eye. This relationship shows that, if the eye is exposed to 2,000 mL (daylight brightness) for 15 sec, the eye has a sensitivity loss equivalent to that of being exposed to 200 mL (15/150 x 2,000 mL) for 150 sec or more. These adjusted values then can be used with the data of Figure 2-68.

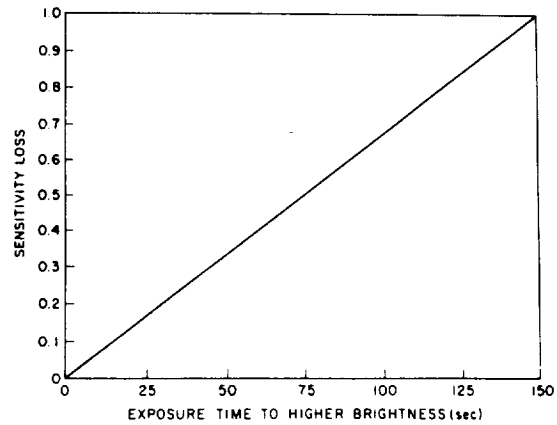


Figure 2-69

Rate of Loss of Dark Adaptation After Exposure to Light. (See text)

(After Mote and Riopelle[306])

The brightness and color of the scope phosphor will determine the specific loss of night vision caused by a CRT scope (413, 462). This may interfere with night vision of a crewman by the effect on dark adaptation or by direct glare of the scope during a visual exercise. The effect of color is similar to that seen on Figure 2-42c. Recovery takes the least time when a red CRT screen is used, only 10 percent longer with a yellow screen, but nearly twice as long with a green screen. The visual characteristics of various phosphors are available (462). The selection of cockpit and instrument color lighting for dark adaptation has been recently reviewed (291, 389).

In CRT displays, detectability of targets of varied contrast and geometric coding may be adversely affected by visual "noise" or "snow" on the scope background. The effects of this noise on the perception of forms in electrovisual display systems have been studied extensively (113, 114). Visual noise with a combined contrast and contour degradation impairs form discrimination to a much greater extent than reducing contrast alone. A typical finding is seen in Figure 2-70. The generation of noise on a prototype electrovisual display as "granularity" of the display was varied, as well as the brightness contrast. Landolt ring targets were used against the variations in background noise to measure the effects of the visual noise on visual discriminations. The variations in granularity of the background affected primarily the clarity of the contours of the visual targets. By variations in the display, it was possible to vary the contour degradation and the brightness contrast. The sharper slope of the solid curves (in comparison with the dotted ones) indicates the greater influence on visual discrimination of the combination of contour degradation and contrast, as compared with contrast alone.

Effects of delay of image motion on target detection using side-looking radars are under study (32). Visual phenomena such as anomalous movement on CRT scopes under certain phosphor conditions are also under study (129).

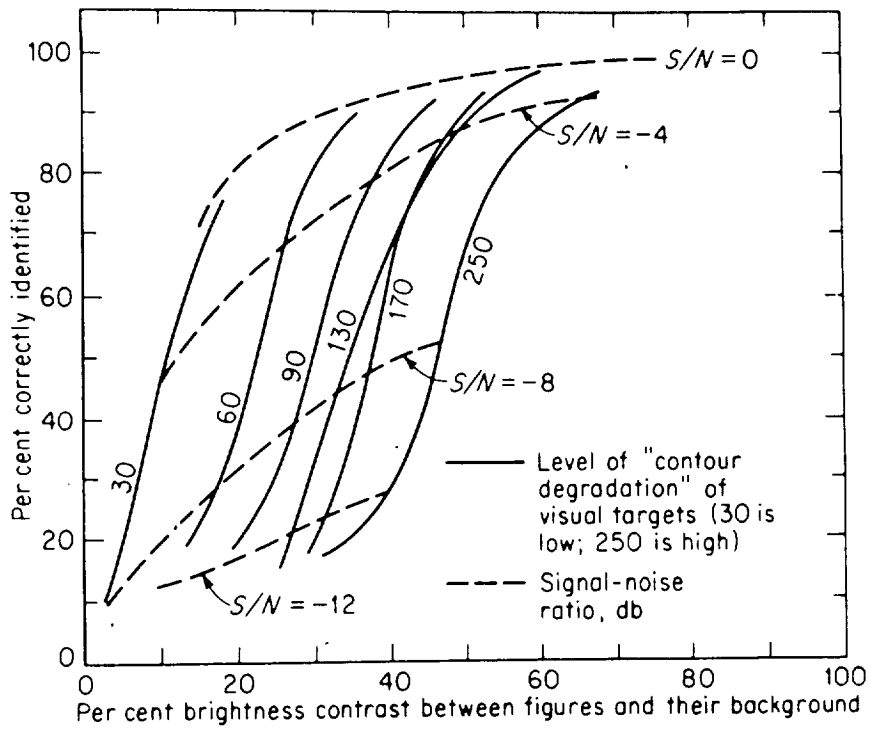


Figure 2-70

Relationship Between Aspects of Visual Noise and Identification of Landolt-Ring Targets on Electrovisual Displays. The Sharper Slopes of the Solid Curves Show the Combined Effects on Visual Discrimination of "Contour Degradation" of the Target Forms Accompanied by Changes in Brightness Contrast, as opposed to the Flatter Slopes of the Dotted Curves Which Represent Essentially Changes in Contrast with "Contour Degradation" Held Constant.

(After McCormick[280] Adapted from Crook and Coules[114])

Complex Visual Displays

Target recognition and acquisition of information may be difficult on complex displays (24, 138, 236, 258, 385, 387, 452). Optical enhancement techniques for visual displays have been studied (422). Displays covering multiple inputs may be color coded (51, 115, 122, 258, 389) and make use of electroluminescent techniques (341). Color mixture functions at low levels of luminance are under study (347).

Visual factors in the design of large scale displays have been evaluated (257). Recent reviews of instrumentation and displays for night visibility (404, 389) and of visual factors in the design of contact analog devices (86) are available. It has been shown that peripheral displays can be used with effectiveness to decrease deterioration of tracking performance which results from visual switching in complex displays of advanced vehicles (420).

Display requirements for prelaunch checkout or launch control of advanced space vehicles (129, 163, 338) and planetary surface vehicles (185) have been outlined.

VISUAL PROBLEMS IN SPACE OPERATIONS

Space operations present several visual problems not usually present on Earth. There are several requirements of a predictive nature needed to optimize contact with exterior visual environment. These data can be used to simulate such visual problems (12, 284). Many of the figures and tables in the previous sections are applicable when supplemented with the appropriate data and concepts.

The following section will review the visual problems of satellite observation, rendezvous and docking, lunar landing, and operations on the lunar surface.

Observation of Other Space Vehicles

It is often of importance to detect orbiting space vehicles from a great distance in order that sufficient time be available to carry out the necessary navigational maneuvers. For a stationary target, the visual range for detection as something different than the surround without identification of its shape, can be predicted, knowing its size, its luminance, the luminance of the background, to which the observer's eye should be well adapted and the contrast threshold for this situation. The details of these calculations have been described (371, 372) and have been covered in Figure 2-23.

A satellite frequently appears as a sunlit object against the background of the space sky which has a luminance of about 10^{-5}nt or 10^{-6}mL. Sometimes a satellite may be seen as a brighter or darker object against the sunlit Earth, the luminance of which depends on how much of the ground is covered by clouds. In rare instances, the nonilluminated satellite may appear against the surface of the sun or against the airglow line. At night it may appear as a moonlit object against the dark night sky or the surface of the dark Earth.

The adaptation of the astronaut is determined by the average luminance of the surface which he is viewing. He probably never observes the same area for more than a few minutes because of his different duties. Since light adaptation requires only a few minutes, the sensitivity of his eyes may rapidly reach a plateau when he is looking at the sunlit surface of Earth or when inspecting the instrument panel. The cabin illumination increases when the window faces the sun or the sunlit Earth. On the other hand, dark adaptation is a slow process requiring at least 15-30 minutes (depending on previous conditions) to achieve a fairly stationary high sensitivity (Figure 2-42 and 2-43). In orbit, a terminal dark adaptation may be difficult to obtain in view of the short range day-night cycle. In a low orbit, there is a shift from day to night and vice versa about every 45 minutes.

Some of the visual ranges may be higher than those computed for vision on Earth for the following reason. When observing the instrument panel first and then looking toward the dark sky, the eyes are adapted first to a higher luminance, for which the threshold was established. (Figures 2-16 and 2-17). When looking out into space, a sudden rise of sensitivity occurs within fractions of a second, known as alpha-adaptation, followed by the

slower beta-adaptation process. During the scanning of the sky the sensitivity of the eyes slowly rises. There are a few data available about sudden changes in adaptation and pertinent studies are still in progress.

The contrast sensitivity may be affected further by the retinal region stimulated, motion, time of exposure of the target and empty visual field myopia (448). In the presence of an empty visual field subjects cannot relax accommodation completely. Accommodation remains in a state of constant activity, fluctuating about a level of from 0.5 to 2.0 diopters. One is unable to focus at infinity if infinity contains no detail subject to sharp focus. Under these conditions, unable to focus farther than a point about 1 to 2 m. away, one becomes effectively myopic by this amount. Empty visual field myopia can increase the light threshold by a factor of log 0.3 or double the minimum visual angle (329, 448). It is difficult to say how serious a factor empty visual field myopia would be in space flights since an astronaut is not constantly scanning a homogeneous field. When looking at the sky, he perceives celestial bodies which are objects for focusing at infinity. Many of these factors are covered in the previous section and are applicable to space operations.

In the present context, these factors are interrelated in a complex way. Uniform sensitivity exists over the retina at the limit of scotopic and mesopic vision (log-3mL) up to at least a 25° peripheral angle. In the scotopic stage there is a steep increase in sensitivity from the fovea toward the parafovea and then a more or less leveling off. The fovea is blind for targets of low luminances. Values determined for parafoveal vision are also nearly correct for a more peripheral region. When the adaptating luminance is above the scotopic level, the trend of sensitivity becomes reversed. Sensitivity is now highest in the fovea and decreases steadily toward the periphery, the decrease steepening with increasing adaptating luminance. Thus, foveal threshold values are not valid in the retinal periphery (see Figures 2-24 and 2-25).

The findings on stationary targets may only be applicable in space when both satellites move with the same speed and in the same orbit. Other situations are possible: the target may move slower than the observer and thus may apparently move backwards, their pathways may cross each other or the target may move toward the observer. For these different situations there are not yet sufficient data available in the literature. The threshold luminances for a point light source simulating a satellite and moving horizontally at an angular speed of 1 to 4 degrees per sec have been calculated (187). On a star-studded night sky as background, the threshold for detection is about 1 stellar magnitude brighter than for detection of a stationary target on a starless background. The difference increased rapidly as vision began to change over to cone or photopic vision. A moving target stimulates not just one point on the retina but successive retinal regions. In scotopic vision, successively stimulated retinal receptors may be of equal or similar sensitivity, whereas, in photopic vision the image of the target will stimulate less sensitive areas as soon as it moves from the fovea. Thus, under these circumstances higher threshold intensities are required. Data on detection times for moving targets in rendezvous are discussed below.

Another variable is the time of exposure. A satellite may be visible for only a limited time, especially in a restricted field of view. This factor is covered in Figure 2-33. Data on sensorimotor latency factors in flight operations are available (52).

Computations of sighting probability for visual search in space have been made (183, 255, 313, 455). Factors which favor probability of success in visual search are: high contrast ratio between target and background, large target size, slow closure or movement rates of the target relative to the observer, and restricted area of search. Factors which reduce probability are: irregular illumination of target, interference with scanning efficiency by other tasks, thickness and clarity of the window glass, low angle of incidence for viewing through window, glare from the sun for some target directions, empty field myopia, and the visual blind spot in each eye. The variables are so numerous that practical use of such calculations must be reserved until more empirical data are available.

Identification of the Shape and Other Details of a Satellite

When an object in space has been detected as a lighter or darker silhouette, some nearer observation distance is required before its shape can be recognized. The recognition of a shape and other details is a complex function of visual acuity. Table 2-71 shows the visual range or the

Table 2-71

Visibility of a Satellite in Space

(After Schmidt[371])

Illumination of satellite	Astronaut adapted to	Visual acuity	Visual angle of critical detail	Visual range of identification, km*
Sunlit, full-phase +F	space sky +F	1.7	35"	5.9
Moonlit, full-phase	night sky	.25	4'	.86
Nonilluminated +F	sunlit earth +F	1.5	40"	5.2
Nonilluminated	airglow line	.25	4'	.86

*For a spherical satellite 5 meters in diameter with visual transmittance of window = .5 and 10% probability of detection. +F refers to a neutral density filter of 0.1 transmittance.

farthest distance at which one can identify the shape of a satellite. The visual range for specific objects can be computed by using curves of Figure 2-23 and by assuming that the visual angle of the critical detail represents 1/5 of the diameter of the satellite (371). At the identification distance, the sunlit satellite is at least 10 times too bright to be observed comfortably (346). Therefore, the transmittance, 0.1, of a neutral density filter was used for the computation. Table 2-71 demonstrates that the shape of the satellite is recognized at about the same distance whether it is illuminated by the sun seen against the night sky or is perceived as a silhouette against the background of the sunlit Earth. The chances for identification

of a moonlit satellite are as low as those of a nonilluminated satellite seen against the airglow line and they are definitely worse for a nonilluminated satellite appearing against the night sky or the night time Earth.

Differences in colors would aid in recognition of details but they are far less decisive than brightness contrast. Visual acuity shows a dependence on the exposure time: a 0.5 to 1.0 seconds exposure is optimal (Figures 2-33 and 2-34). The recognition of a shape also depends on psychological factors such as previous experience and training of the observer. A familiar form is resolved more easily than an unfamiliar form; an expected form, more easily than the unexpected (48, 49, 52).

Motion of a satellite relative to the star background is the factor most helpful in its detection. The threshold for perception of motion in laboratory studies under optimal conditions is equal to 1 to 2 minutes of arc per second. The displacement threshold (the minimal angular displacement required to perceive a motion) in presence of stationary objects is 20 seconds of arc. In the absence of fixed comparative objects the values are higher. The star-studded sky is then an appropriate background for the detection of a moving satellite (See Figure 2-39). The motion threshold is affected by the same variables as the other visual functions mentioned, e.g., background and adaptation state of the observer, intensity of the target, retinal region stimulated, size of the target, and exposure time up to a certain critical value.

In the absence of other lights, it has been observed that a stationary light after at least 9 seconds of fixation in an empty surround starts to move in an erratic manner. This optical illusion, known as "autokinetic movement", may also play a role when a satellite is observed against the dark sky (181). The vestibular apparatus appears to play no part in its genesis but eye muscle imbalance may play a role (149, 164). The operational significance of this subjective phenomenon is not as yet clear.

In space operations, the estimation of the distance of another spaceship is of crucial importance. The recognition of the distance is a complex function which involves the integration of immediate visual impressions and previous experience (4, 179, 180, 182). For a moving light point far out in space, many cues of depth perception are invalid, especially the primary factor of stereopsis. An important factor for recognition of an absolute distance, that is a distance with reference to the observer, is the presence of a terrain. In case a terrain is lacking, distance judgment becomes unreliable and, without size cues, only relative distances are recognized, namely that one object is nearer than the other. An important empirical distance factor is the apparent size. In order for this factor to give information about the distance of an object in a homogeneous surround, the real size of the object must be known. When the actual size of the target is unknown, its distance will be indeterminate, since the same angular size can correspond to a small object nearby or a large object at great distance (See Figure 2-74).

One secondary distance factor is motion perspective or motion parallax or the gradual change in the rate of apparent displacement of objects in the

field when the observer is moving. When fixating the horizon toward which the locomotion is aimed, the ground below shows a flow opposite to the motion of the traveler (161). The visual field appears to expand anteriorly from a stationary focus to which attention is aimed. The visual field behind contracts inward to a focus. The farther objects have a slower rate of speed than the nearer objects. The astronauts repeatedly mention the flow of the surface of Earth opposite to the direction of their orbit. The drift is quite apparent over clear areas or broken clouds whereas a solid cloud cover with no pronounced texture mediates a very slow floating feeling. When gaze is fixated on the target satellite, it should show no such parallactic motion because the pursuit movements of the eyes keep its image on the fovea, unless its actual motion is so fast that it makes fixation impossible. The celestial bodies, as more distant objects, should show a parallactic with-motion. When the gaze is fixated on a star, the satellite as a nearer object should show a parallactic against motion which may conflict with its actual motion.

Another empirical factor in distance recognition is the aerial perspective; that is, the progressively increasing haziness of objects as their distance from the observer increases (gradient of haziness). The clearer the outline of an object, the nearer it is perceived. In space there is no gradient of haziness. The light and dark areas on the surface of a satellite produce sharp boundaries (367). Clearer contours and clearer details may cause an underestimation of its distance, in comparison to what is known from observation on Earth. This, in turn, should make it appear smaller because the retinal image actually corresponds to farther distance. As long as the satellite subtends visual angles large enough to affect the eye as a luminous surface, its brightness is determined by its luminance and is independent of its distance, but, as soon as the visual angle becomes so small that it affects the eye as a point light source, its brightness decreases with increasing distance and thus might serve as a distance cue (Figure 2-18).

Visibility of Objects on Earth from Spacecraft

Theoretical aspects regarding the detection of Earth targets from space with and without periscopic aid have been covered (313). Quantitative data obtained during actual space flight are now being processed (131). An example of the findings on revolutions 17 and 31 of Gemini VII are presented in Figure 2-58. Computer programs are being prepared to allow prediction of Space to Earth visibility (130).

Vision in Rendezvous and Docking

The visual tasks associated with rendezvous and docking are summarized in Table 2-72.

Table 2-72

Visual Rendezvous Operations

(After Pennington and Brissenden[336])

PHASES OF RENDEZVOUS	VISUAL TASKS	TARGET PARAMETERS
1. ACQUISITION	DETECTION	INTENSITY, COLOR SIGNAL SEQUENCE
2. ESTABLISHMENT OF INTERCEPT	ANGULAR RATE DISCRIMINATION	MOTION CUES
3. RANGE AND RANGE RATE ESTIMATION	"	"
4. BRAKING OPERATIONS	DISTANCE AND CLOSURE RATE JUDGEMENT	SIZE, SHAPE, MOTION CUES
5. DOCKING	ATTITUDE	ASPECT

Visual information for rendezvous, docking, and navigation has been outlined (19, 33, 67, 68, 69, 205, 207, 228, 229, 230, 263, 264, 269, 334, 335, 337, 349, 350, 370, 381, 461). Visual data can be used to predict accuracy of navigation techniques proposed for different phases of space flight (198, 200, 288, 289). These show that visual control is efficient in many areas and can be used in secondary or backup control techniques. Space flight data suggest the critical nature of visual problems in rendezvous and docking maneuvers (313).

Acquisition

Visual observation from another spacecraft of a satellite moving against a starfield background has obvious operational importance in any rendezvous mission where the target satellite must be detected and located to effect terminal guidance. The operator may be required to act as a backup system in the event of radar or other failure. It has been shown that a pilot can accomplish rendezvous using only visual sighting of the target position (264). Also an accurate knowledge of visual detection ranges can aid in planning launch time to obtain favorable illumination during acquisition phases.

The ability of the observer to detect a target satellite as a point source target moving slowly in a starfield has been covered above and quantified by recent studies (381). In contrast to detection problems on Earth, the target is identical in appearance to the other objects from which it is to be distinguished. If the satellite is illuminated by solar or Earth light and the target intensity is within the range of visible stellar intensities, only its motion relative to the fixed stars and actual presence of a new object in the

starfield can serve as cues to the observer. (An asymmetrical rotating satellite may produce a variation of intensity with time.) The surface characteristics of a given target, the viewing angle and the direction of incident light are needed to determine its photometric intensity. The problem is compounded by the fact that the field of view, background luminance, adaptation level of the observer and allowable search time will influence an observer's detection performance. During a typical transfer orbit, a change in illumination geometry and line-of-sight angular motion occurs (314). Even if the terminal phase occurs in solar illumination, the target may be less visible than it was before the terminal phase, if for example, the target moves between the chaser and the sun.

For the acquisition phase of rendezvous, several studies have been published on detection of a moving point source against a starfield. Given sufficient time, it is possible to see an isolated star of magnitude 8.5 (See Figure 2-9). However, in a field of stars the threshold of perception is closer to a 5th or 6th magnitude star, the former being equivalent to $10^4 \mu\mu$ lamberts (336). (See Table 2-71 and the discussion of Figures 2-9 and 2-12.) Dark adaptation (Figures 2-42 and 2-43), target surface features (287), color (Figures 2-28, 2-29, and 2-30), and intermittency (Figures 2-33, 2-34, and 2-35) of the acquisition lights must also be taken into account.

While the flash duration influences the apparent intensity of the light, the flash rate influences the ease of acquisition, and these two factors influence the power consumption required for the beacon. The rate must be slow enough to permit a flash duration not requiring excessive power, but still fast enough so that at least several flashes will occur during the pilot's search time of the target area. For example, in evaluating a flashing light for use in a proposed orbital acquisition and tracking experiment, it was found desirable to flash at about one cycle per second, and this appears to be a good, representative flash rate (336). The ability of Gemini and Mercury pilots to acquire and track flashing beacons is still under study (314).

The effect of angular velocity and number of background stars on detection performance has been studied (461). Angular velocities from 0 to 3.2 mrad/sec(0.18°) were used and the number of stars varied from one to six in a visual field of 10°. The subjects were required to indicate the direction of movement out of five possibilities (i.e., toward each corner and zero). Response times varied from about 2.5 sec to 40 sec over the range of velocities. Significant first order interactions were found among all combinations of subjects, number of stars, and velocities. For fields composed of one, two and three stars, the subjects reported an inability to establish a reference for determining the direction of motion. Errors in reporting direction increased with a decreasing target rate.

The effects of target intensity and velocity on the subject's ability to detect a point source target when a different starfield was used on each trial has also received study (401). The range of conditions included photopic and mesopic targets (+2 to +5 magnitude). As part of the same study a second experiment was conducted to investigate the effects of target intensity, velocity and practice on detection performance when the same starfield was used on repeated trials. Both experiments showed that target angular rate

strongly affected detection time, but this dependence decreased with practice. Memory for the starfield played an important role in target detection. By the last session of the experiment, differences in detection time between different conditions of target velocity and intensity had decreased. Variations in target intensity produced a variation in search time for the initial sessions in both experiments, but the magnitude of variation decreased with practice. In terms of detection time, there was apparently little difference in time for a mesopic target as compared to that for a photopic target. Recent studies indicate that detection time also depends upon target velocity, starfield density and field of view (381). Differences in target velocity produced the greatest variability in performance with an average detection time of 220 sec for 0.1 mrad/sec rate and 45 sec for 2.4 mrad/sec rate. There is an appreciable difference in mean detection time between the two modes of starfield presentation -- 15 sec for the same starfield background contrasted with 150 sec for the unique or novel background. Detection time for the unique starfied group depended on target velocity and target intensity but for the group exposed to the same starfield, detection time became independent of these variables after a number of trials. There was no positive or negative transfer of training from one type of starfield presentation to the other.

On the basis of these results two models were proposed to explain the observer's search strategy for each type of presentation. In novel or unique starfields, the observer initially uses brief fixations and rapidly scans the starfield to detect the moving target. If this strategy fails he then fixates on specific clusters of stars and memorizes their pattern, later returning to each cluster to determine if a change in the pattern has occurred. When the observer detects a change he identifies the target by ascertaining the change in a relative position of one of three or four stars forming a pattern. For searches in the same starfield, the observer uses only two or three fixations, detects the new object by comparing the memorized pattern with the presented pattern.

Unaided visual search has been compared with search aided by a finely ruled reticle in a telescope (19). The reticle caused the target to blink as it moved across the field. A $22^{\circ}\ 38'$ starfield was used with the target always appearing in the central 12°. An average density starfield (not stated) was used with a range of stellar magnitudes from +0.5 to +6.0. The target intensity was +3.0 magnitude. The subjects were given two trials with and two trials without the reticle. For a target velocity of 0.1 mrad/sec, the mean detection time was 169 sec without the reticle and about 40 sec with the reticle. The number of misses and incorrect identifications, if any, were not reported.

Optimization of search strategies under variable starfield backgrounds of a moving spacecraft remains to be performed.

Establishment of Intercept

One technique for the intercept phase of rendezvous is to bring the angular rate of the line of sight of the target vehicle in an inertial reference system to zero and then to control closure rate to effect a safe rendezvous. In simulations utilizing this technique with visual references for background

and target, it was found that pilots could detect the target and establish the intercept course (228). The terminal rendezvous maneuver can be controlled even without instruments for range, space angles, and time derivatives of these parameters, if the pilot has sufficient background reference to make angular measurements on the order of 1 millirad (69). A simple table or slide-rule type of computer is sufficient for converting the angular measurements to range and range rate. An accurate instrument, however, is required for obtaining the 0.1-millirad/sec line-of-sight rate needed to perform visual rendezvous. This instrument must have angular resolution equal to 1 millirad over an observation time of 10 sec or more, and a timer that can be read to within 0.1 sec.

Laboratory studies have shed some light on the critical aspects of this tracking problem. The effects of target angular velocity and of initial separation from a reference point on the time to identify direction of motion of a point source have been determined (68). The starfield background consisted of 106 stars in a 22° field with random separation angles. Stellar intensities were not given but the moving spot was slightly brighter than background. Tests were conducted with dim light spots on a black surface, and were estimated to have intensity equivalent to fifth-magnitude stars. The light spots subtended 1.7 milliradian but definition was such that the outer annulus of about 0.2 milliradian was fuzzy. The moving spot was slightly brighter than the background stars. The target was centered in a 3-star triangle or a 4-star square and different directions of motion were used. Initial separations from a reference star ranged from 12.5 to 60 mrad (0.71 to 3.4 degrees). The subjects knew the location of the target so that search and detection were not required. The subject's task was only to report the direction of motion. Target velocities were varied from 0.1 mrad/sec (0.057°)/sec to 2.0 mrad/sec (1.14° sec). The time to detect the target varied from 2 sec to 35 sec for rates from 0.1 to 2.0 mrad/sec.

Figure 2-73 shows results of one series where the rate of motion is plotted against the overall average detection time for six subjects.

If the initial spacing is 12.5 milliradians, a pilot can detect an angular rate of 0.1 milliradian per second in about 10 seconds for a 1-milliradian traversed angle. Figure 2-73 also shows a tendency to recognize motion to the right more readily than motion to the left for the closest initial positioning of the objects. One can calculate from these data the angles through which the object moves during the time required to detect the motion.

If the target moved across the reference background in random directions, the task of identifying both the

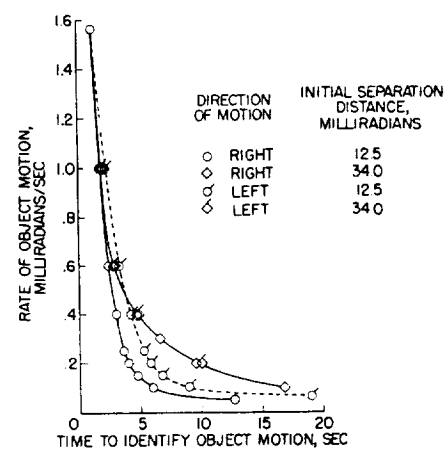


Figure 2-73

Typical Angular-Rate Perception

(After Brissenden[68])

existence and direction of motion became more difficult than just detecting motion in a predetermined plane. The time required for this task when only the correct estimates of the direction of object motion are used is available. Fatigue is a distinct factor in these studies.

Figure 2-74 is typical of results of how well subjects can detect separation from a superimposed condition at various speeds. The object and the reference both subtend 1.7 milliradians. The "detection" curve is parallel to the actual separation curve at speeds of separation above 0.1 milliradian per second. At 0.1 milliradian per second, detection of separation required 17 seconds. At rates less than this, detection times converged on actual times required for the objects to separate, and reaction time was such a small percentage of the test time that its effect was secondary.

Errors in reporting the direction of motion increased almost linearly from 2% for the target initially superimposed on a star to about 25% for 30 mrad of initial separation but decreased little beyond this separation. It was not stated whether or not the detection times included incorrect responses.

Range, Braking and Docking Phases

After acquisition, correction to an intercept course, and initial braking have been accomplished, (leading up to something less than two miles separation distance between the chaser and the target) the final braking and docking phases are initiated. The pilot observes aspect and closure rate as information to complete the maneuver. The visual conditions here are entirely different from those of the early phases where the target was seen as a point source.

When target objects are nearby, change in visual angle, size cues, shapes, lighting patterns, and color becomes more significant variables. This information is sufficient to enable the pilot to control the range and range rate by direct visual contact, while orienting his vehicle for the docking and final latching maneuver. The appropriate data in section 2 can be used for design prediction as can more specific data from other sources (20, 21, 38, 43, 46, 50, 53, 77, 92, 139, 162, 166, 167, 168, 169, 170, 171, 172, 173, 174, 201, 405).

The apparent size of the target vehicle is used by the pilot to estimate the separation distance between the vehicles. The ability of the pilot to judge object separation distance with no visual cues except the apparent size of the target is known (336). After a period of dark adaptation, subjects were asked at night to estimate the range of several models of known size placed at random distances. Figure 2-75 shows the average distance judgments of several observers for various configurations. The solid line represents perfect estimates. Beyond 500 feet, estimations were better than expected, but with a tendency towards overestimating the range of the large objects and underestimating the range of the smaller target objects. All estimates (except for the balloon) were fairly accurate from 500 feet in to zero. The effects of illumination, color, and aspect are currently being studied.

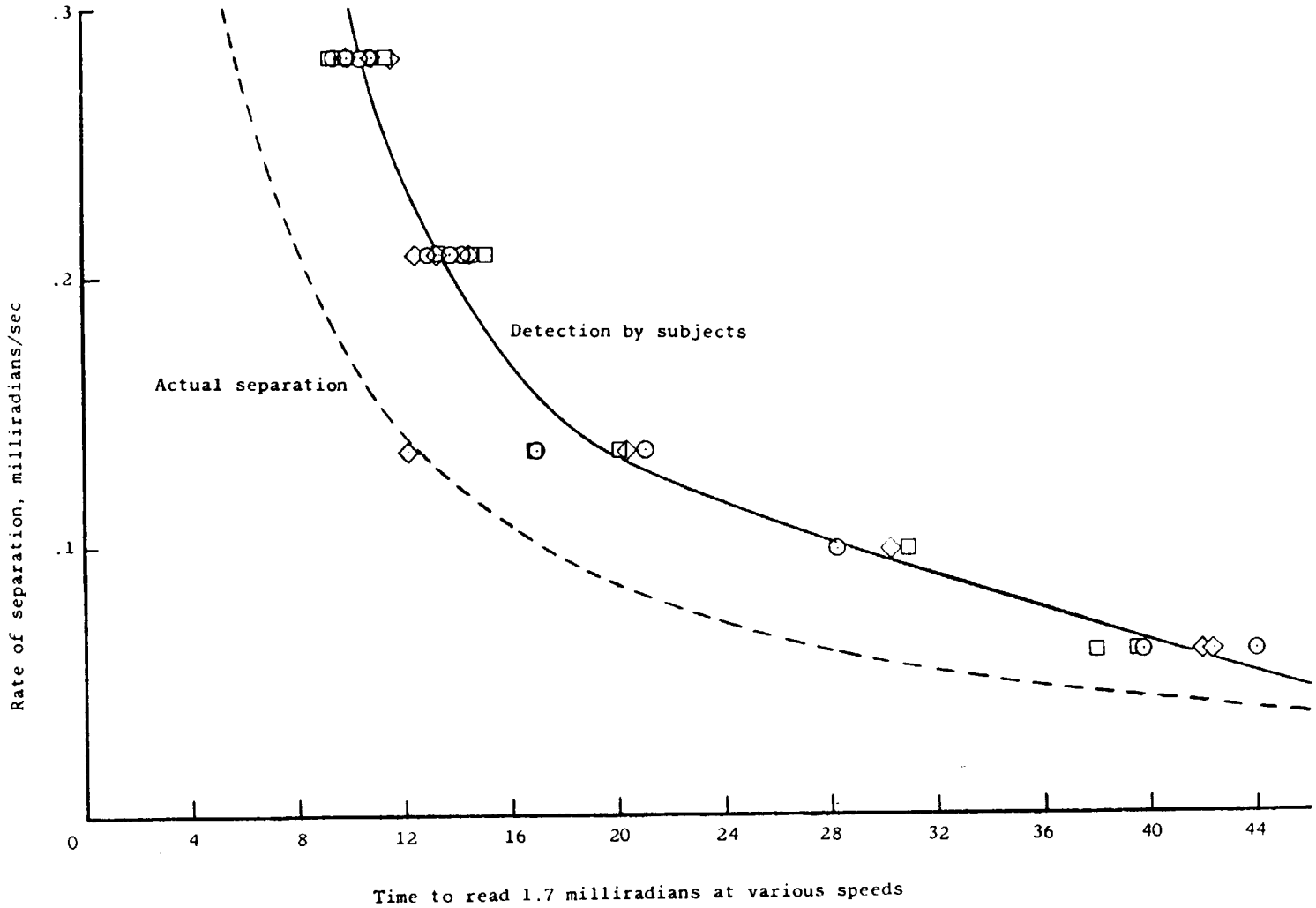


Figure 2-74

Typical Plot of Maximum Separable Acuity. 1.7-Milliradian-Diameter Object Initially Superimposed on Background Reference of Same Size.

(After Brissenden[68])

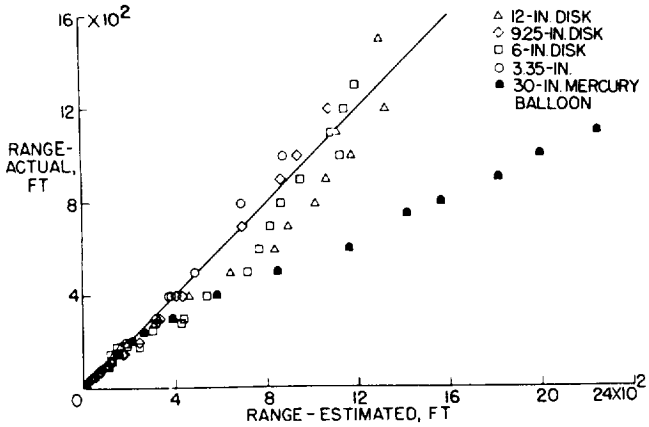


Figure 2-75

Distance Judgement with No Visual Cues Except Size of Target

(After Pennington and Brissenden[336])

Estimation of velocity is a key factor in visual docking (78). In the visual-docking maneuver the rate of change of size can be used to determine the rate of closure between two vehicles (263). Attention has been given to the question of visual sensitivity when the target is in motion along the line of sight as an important factor in judgment of closure rate. Under these conditions the problem may be conceived in terms of the discrimination of a change in angular size over time. In a dark field, the threshold as a function of the velocity and luminance of the target has been determined (23). The conditions approached those of a homing and docking maneuver, since the object, a 3.5 in. luminescent lamp, subtending an angle of about 40' of arc, corresponding to the angle subtended by a 5 ft object viewed from about 430 ft. Detection improved as the luminance increased from 0.001 to 0.1 ft L, with little added improvement when the luminance was raised to 1.0 ft L. The rate of movement also affected the threshold, the amount depending upon the threshold criterion used. Movements were detected when the visual angle increased or decreased, by amounts ranging from about 1.5 percent to about 8 percent. Using the 95 percent correct threshold criterion, the detection threshold was between 8 percent visual angle change (at slow speeds) and 5 percent (at higher speeds). The threshold generally decreased as the criterion was relaxed, the 65 percent correct criterion yielding thresholds of about 1.5 percent.

It has been predicted that at closure rates of about 3 ft/sec, detection of movement would occur with 95 percent reliability when the distance traveled was about 8 percent of the initial distance, while at rates of about 20 ft/sec detection would occur when the distance was about 5 percent of the initial distance. Assuming that thrust is applied on the basis of such detections at the outset of a homing and docking maneuver, one may anticipate between 5 and 8 percent error in the distance at which initial thrusts were applied to establish the approach rates. These would be expected to undergo adjustment as approach continued.

A more recent study has been primarily concerned with vertical descent to the lunar surface, and in the simulation a projection of the lunar surface was servo-driven in a closed-loop system for closure cues. The pilot applied a braking thrust to stop the apparent closure velocity; the thrust voltage was fed to an analog computer and then to the landscape-

projector drive system. The results seen in Figure 2-76 obtained for one observer over the range of visual angles considered may be applied to docking. The ratio of closure rate $\dot{S}$ to distance S, define (for this particular test subject) the boundary of this $\dot{S}/S$ ratio. This threshold was based on a reply time of 2 seconds dictated by time lags inherent in the test procedure. The figure is of interest because it shows that the maximum perception of closure occurs at visual angles, as subtended by the target outline, from 70° to 90°. This boundary agrees with an analytical derivation of the relation between S and $\dot{S}$. For this subject, it was found that a representative value for the closure threshold $\frac{\dot{S}_{min}}{S}$ fell between 0.013 and 0.016. In docking, the pilot should be able to judge the closure rate to about 0.15 feet per second from a distance of 10 feet. It is clear that estimation of closure rates is subject to strong training effects (22).

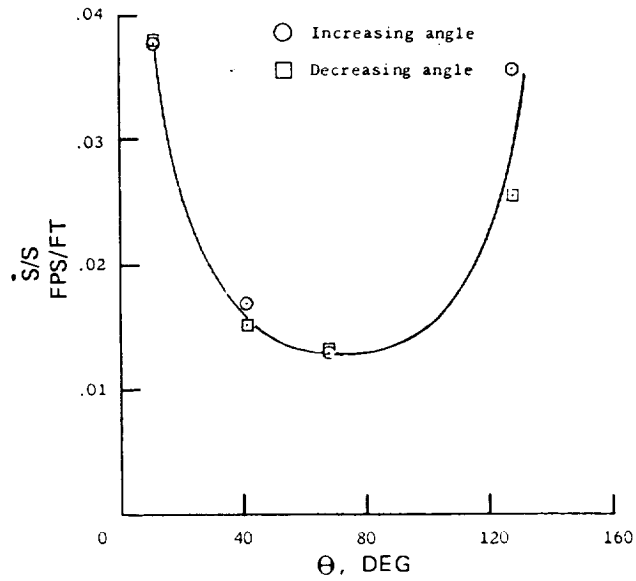


Figure 2-76

Threshold of Velocity Perception

(After Lina and Assadourian[263])

Simulation studies have added much to the use of many of these concepts in operational design (33, 98, 205, 206, 228, 265, 269, 334, 337, 348, 349, 350). Operator performance in the control of remote maneuvering units during satellite inspection is currently under study (96, 97). Most translation errors existing at termination of pilot-controlled docking appear to be caused by visual cues (337). Pilots are capable of visually aligning the Gemini and Agena within about 1° of roll and 2° of pitch and yaw using direct (acceleration-command) control mode. Inaccuracies tend to arise from parallax problems in observation of indexing bars and by inability to separate attitude and translation errors.

Oscillation of visual target vehicle can effect efficiency of docking in the visual mode (349). A brief study has been made with a fixed-base simulator employing closed-circuit television to determine the effects of target sinusoidal oscillations in three angular degrees of freedom on pilot-controlled Gemini-Agena docking. Flights were initiated at a range of about 300 feet and were performed by using both the rate-command and direct (acceleration command) attitude-control modes with only visual observation of the target for guidance. Vehicle mass and moments of inertia simulated the parachute configuration of the Gemini spacecraft with a one-half fuel load. The results of the study apply to a fully illuminated target with rear-mounted visual-aid bars for additional boresight information and are as follows:

• For docking flights using either the rate-command or direct attitude-control modes, task performance and pilot ratings comparable with those for a rigidly stabilized target were obtained with the target oscillating at ± 5° amplitude in each of three angular degrees of freedom at oscillation periods of 160 seconds or greater. Fuel consumption and flight time increased, pilot ratings were less favorable, and the percentage of successful dockings decreased as the period of the oscillations was reduced below 160 seconds.

• For the rate-command, attitude-control mode, limited results on the effect of oscillation amplitude indicate that for an amplitude of 2.5°, target oscillations have little influence on the docking task except at small values of period (30 to 40 seconds or less) where docking-ring velocity tolerances can more easily be exceeded. For the amplitude range between ± 2.5° and ± 10°, increasing the motion amplitude for a given value of period (below about 120 seconds) results in increases in fuel used, increases in flight time required, and less favorable pilot ratings.

• Suggestions are available for optimizing docking cues during day and night operations (269, 284, 337). No concrete data are as yet available on the effect of sunlight and glare on docking control. More data are required on star navigation capabilities in rotating vehicles and the effect of glare on this function (see Figure 2-46).

• Visual aspects of lunar orbit establishment and translation and hover maneuvers over the lunar surface have been studied and preliminary simulator data are available (294, 295).

Visual Requirements for Lunar Landing

The visual parameters for establishing a circumlunar orbit and accomplishing survey of the lunar surface in preparation for landing have been determined (105, 295). In preparation for landing, the rate at which the objects traverse the visual field also has to be taken into account (see Figures 2-39 and 2-40). Study of the effect of stimulus velocity on acuity thresholds revealed that the threshold value increased by a factor of four as stimulus velocity was increased to 140° of visual angle/sec (274). Subjects were required to identify the orientation of Landolt C stimuli exposed for 0.4 sec. Acuity thresholds increased from 3 to 11 min of arc as stimulus velocity increased. Beyond 140°/sec the perceptual task was impossible for most subjects; stimuli were reported blurred beyond recognition.

For the clear perception of a contour, however, the perceptual response breaks down at lower rates of target movement. A contour subtending 30 min of visual angle and moving horizontally across a 5° visual field could not be perceived for rates greater than 15°/sec (390, 391, 392). Presenting the contour in a stationary position a few hundred milliseconds prior to the movement, permitted the contour to be perceived at higher rates. It was observed, however, that for velocities beyond 40°/sec contour perception was impossible for any amount of stationary exposure time. In addition,

increasing the contrast and illumination level improved contour perception for higher velocities.

The velocity of lunar landmarks across the visual field is determined by the (a) orbital and de-orbital speed, and (b) altitude of the spacecraft. At speeds of 5000 ft/sec and altitudes ranging from 50,000 ft to 100 miles the maximum apparent velocity of lunar objects is slightly less than 6°/sec, which is within the range of human capability for contour perception (350). The rotation of the moon is not considered in these calculations since the speed of rotation is only 15.18 ft/sec at the equator and contributes a minor effect on the apparent velocity of landmarks perceived from the spacecraft. It appears that angular motion of the target should present little difficulty to the astronaut in locating and identifying lunar landmarks for initiating a deorbit and landing sequence on the moon with unaided eyes.

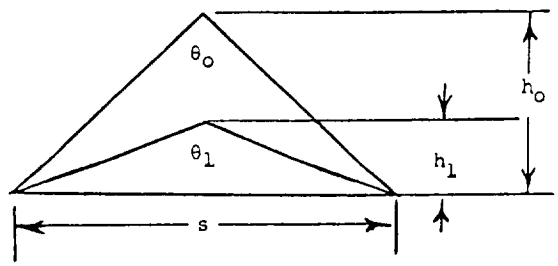
In planning for manned lunar landings, one must consider the capabilities of a pilot to make final corrections required to land a vehicle on the lunar surface. For the lunar landing, judgment of vertical velocity has fundamental similarity to the necessary ability displayed by a helicopter pilot in making a vertical landing. However, in the case of the helicopter landing, small distances and velocities are involved, whereas the lunar landing deceleration might, under emergency conditions, encompass much larger distances.

Human judgment of speed (or vertical velocity) relative to a two-dimensional object is based on rate of change of the subtended visual angle. Analysis of the problem is presented as follows (263):

Assuming,

h	distance perpendicular to reference plane, ft
$\dot{h}$	velocity normal to plane, ft/sec
$\dot{h}_{min}$	threshold perception of velocity, ft/sec
s	distance on the reference plane between features which are equally spaced from the perpendicular line of sight, ft
Δt_{max}	maximum image-retention time of the eye, sec
θ	total visual angle which is subtended by the reference base-line distance s, radians unless otherwise indicated
$\Delta\theta_{min}$	angular resolution of the eye, radians
$\dot{\theta}$	rate of change of visual angle, radians/sec
$\dot{\theta}_{min}$	threshold perception of visual angular rate, radians/sec

a descent from height h_o to height h_1 will result in an increase of the visual angle from θ_o to θ_1 when an object of size s on the ground is seen. The visual reference distance s may be the size of a single object such as a boulder or it may be the distance between two objects. In the case of a



descent above a reference circle or crater, the increase in visual angle would be seen as an apparent growth in diameter.

The relation between height size of object, and subtended visual angle is

$$\tan \frac{\theta}{2} = \frac{s}{2h} \tag{14}$$

The threshold of perception of relative velocity is related to the threshold of detecting visual-angle rate. The relationship, obtained by differentiating equation (14) with respect to time, is

$$\frac{\dot{h}_{min}}{h} = -\dot{\theta}_{min} \left(\frac{1 + \tan^2 \frac{\theta}{2}}{2 \tan \frac{\theta}{2}} \right) \tag{15}$$

and can also be expressed

$$\dot{h}_{min} = -\dot{\theta}_{min} \left(\frac{h^2}{s} + \frac{s}{4} \right) \tag{16}$$

by substituting equation (10) in equation (15). If $\dot{\theta}_{min}$ is a constant and has no dependence on visual angle, then for the case of a single reference object, the most sensitive velocity cue will be at impact with the surface. When the view is unobstructed, however, distinctive terrain features may be seen over a wide range of visual angles. In this case, it is necessary to find the object size at a given height that will minimize the vertical velocity at the threshold; this is done by differentiating equation (16) with respect to s, holding $\dot{\theta}_{min}$ and h constant, to give

$$\frac{d\dot{h}_{min}}{ds} = -\dot{\theta}_{min} \left(\frac{-h^2}{s^2} + \frac{1}{4} \right) = 0 \tag{17}$$

$$h = \frac{s}{2} \tag{18}$$

The maximum sensitivity to velocity would therefore be provided by terrain features on a 90° visual cone. However, for human control, it is the product on the right side of equation (11) that must be minimized ($\dot{\theta}_{min}$ cannot be assumed a constant with no dependence on θ). Measurements necessary to determine variations in the threshold of the angular-velocity perception of the eye over a range of visual angles have been made (263). The threshold is defined as the minimum angular rate that can be detected visually with a high degree of probability in 2 seconds. Figure 2-76 and discussion cover the results of these studies. These values seem reasonable in view of human visual resolution and maximum major retention times. Additional helicopter descent studies indicate the $(\frac{\dot{h}}{h})$ values are conservative enough for design assumptions (263). These data can also be used for calculation of the point on approach path in lunar landing where emergency visual mode with velocity detection may be brought into play.

Visual determination of altitude on the lunar surface has been simulated (262). Surface feature techniques, when the surface feature is viewed from directly above, seems considerably more accurate for altitude determination than do horizon-matching techniques.

Visual Performance on the Moon

The lunar optical environment has been covered in section 1. Figure 2-17 shows the manner in which contrast and size of objects are related at a wide range of adapting luminances. The near coincidence of the curves at 1000, 100, and 10 mL for objects subtending 10 minutes or more is important to note, for it indicates that eye-protective filters which transmit 10% total or one percent of visible light will not significantly impair contrast discrimination at the higher ambient levels of field luminance. It is clear that the expected luminance levels on the lunar surface (Fig. 2-10 & Table 2-11) are, in the main, well within the operational tolerances of ordinary seeing. There are, however, certain special properties of the lunar visual environment which are unlike any naturally-occurring terrestrial ones (410).

The lack of a lunar atmosphere has several important consequences for the lunar explorer. The first consequence of a missing atmosphere is the absence of diffused light. Shadowed parts of the moon's surface will be very black; the contrasts in the scene will be extremely high and it seems likely that details of the shadowed areas can only be seen by use of some reflective device or auxiliary light source. Another property of the atmosphere on Earth, generally known as atmospheric haze, is habitually used in the estimation of distance and size of features. Since this cue will not be available, and because objects of familiar size may not be available for direct visual comparison, it is believed that the judgment of size and distance will have to be aided by special devices (theodolites, rangefinders) and by special observing techniques (motion parallax), at least at distances where man's accommodation and convergence cues are inoperative and stereopsis no longer helps. Correction for "irradiation" factors must be considered (194) (see Figure 2-49). Simulated studies in dust-free environments suggest some of the illusions which may arise (367).

Distance estimates of surface and flying objects on or near the lunar surface may offer some difficulty because of the unusual lighting conditions. Size, distance, motion and numerosity cues must be considered in analysis of the problem (153). (See also references on the discussion of range estimates during braking and docking maneuvers.) The use of these cues in night operations is another problem which needs further study (417).

Since the sky above the horizon will appear essentially black (unless the Sun or Earth is in the field of view) the adaptive capabilities of the man on the lunar surface may be taxed and his visual performance under such conditions cannot confidently be predicted from existing data (410). For the sunlit and earthlit conditions, the highly directional nature of the illumination will, especially at low angles, combine with the low average surface reflectance to produce wide extremes in the appearance of the terrain (112) (Figure 2-11). Small change in the sun's azimuth and elevation markedly alters the contrast conditions. With an apparent luminance of around 6.4×10^8 ft-L, and subtending a half degree, the sun constitutes a glare source of tremendous magnitude. If the man on the lunar surface must operate with the solar disc in his visual field, it is imperative that suitable protective devices be provided which will prevent discomfort or temporary or permanent visual disability. It has been argued that the man will always operate so as to avoid looking into or near the sun, but we must recognize the probability that accidental exposure will occur. Figure 2-46b suggests that an attenuation factor of about 10^5 will be required for direct viewing of the solar disc without discomfort. Furthermore, the eye-protective devices which have been proposed are far from ideal from the visual standpoint, tending to introduce contrast and acuity losses by reason of scattering or distortion (410).

Other potentially serious glare sources may be introduced by man himself. The need for thermal regulation of lunar excursion vehicles and, eventually, fixed habitats, has dictated that their surfaces be so treated as to be highly reflective. These surfaces are likely, therefore, to be very much brighter than the surrounding scene, especially if seen partly or wholly against the dark sky and may produce serious glare problems and temporary flash blindness. The reciprocity law and visual acuity during recovery should be confirmed under specific luminance x time conditions expected for lunar surface operations.

Preliminary data are available on performance of vision-based tasks in a lunar light simulator (376). The most unfavorable situation occurs when the astronaut's body or other obstacle blocks off light to the task equipment, creating deep shadows. Performance time decrement associated with control tasks varies between 18 and 50% under these conditions. Backlighted panels and display markings and reflecting bezels are recommended. Storage areas or containers require more lighting than in equivalent Earth design. Visual simulation for evaluation of lunar surface roving vehicles is currently under study (427).

Visualization of a vehicle in orbit as it appears near the lunar horizon is required in order to compute a launch time for optimum rendezvous, i.e., rendezvous in a direction away from the sun and prior to entering the

moon's shadow. In this case the astronaut is looking toward the sun. The minimum angle of separation between the command module and the sun for detectability, therefore, appears to be a function of two variables, viz., the brightness of the command module and the degree of impairment of visual resolution due to the glare effects of the sun. The surface of the moon, also a glare source, does not offer a serious problem since the average reflectivity coefficient is relatively low and methods for shielding these reflections are readily available, e.g., binoculars. The data on minimal angle of resolution (MAR) for two small luminous objects may be used in evaluating this problem and the "irradiation" factors of Figures 2-47 to 2-49 (194, 325, 326).

B. ULTRAVIOLET RADIATION

The major source of ultraviolet radiation expected during a space mission is the sun. Transmission of light by the atmosphere obeys the following equation very closely for any given wavelength, λ:

$$I_\lambda = I_{o\lambda} \, e^{-m_\lambda \sec z} \qquad (19)$$

wherein I_λ is the intensity of radiation of wavelength λ arriving at the surface of the Earth, $I_{o\lambda}$ is the intensity of this radiation arriving at the outer margin of the Earth's atmosphere, m_λ is dependent only on λ and z is the angle which the sun subtends with the zenith, called the zenith angle. The length of atmosphere through which the sun's rays must pass (air mass) is directly proportional to the secant of z. The magnitude of m determines the extent of variation of the intensity I of any wavelength with zenith angle, and hence with latitude, season and time of day. For wavelengths for which m is large, the effect of increasing zenith angle is greater than for wavelengths for which m is small. An idea of the effect of zenith angle on the spectrum of sunlight at sea level may be gained from Figure 2-77 where curve 0 represents the spectrum of sunlight outside the Earth's atmosphere, curve 1 with the sun at zenith, and curve 2 with the sun at 60° from zenith (300). The strong effect of ozone absorption is seen at the short wavelength (ultraviolet) end of the spectrum; the effect of the absorption bands of water vapor, in the long wavelength (infrared) region. Detailed data on solar light absorption are available (250, 354).

The transmission of light of a given wavelength by an absorbing system in which scattering of light is negligible, may be described by Lambert's Law:

$$I = I_o \, (1 - R)^2 \, e^{-\alpha t} \qquad (20)$$

where I_o is the intensity of the light entering the system. I is the intensity at depth t, α is a constant generally called the absorption coefficient, and R is the reflective coefficient.

In a system where there is a good deal of scattering, such as human skin, an equation of similar form may be applied:

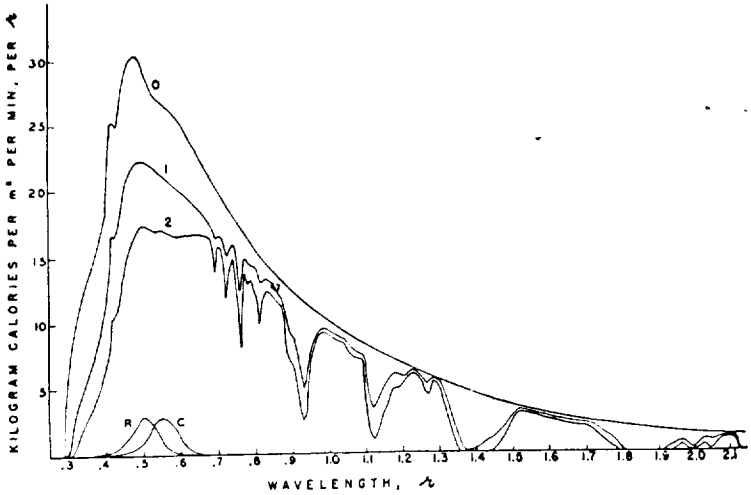


Figure 2-77

Spectral Distribution of Sunlight

0 - outside earth's atmospheres

1 - at sea level with sun at zenith

2 - at sea level with sun at 60°

R - relative sensitivity of the human eye, scotopic vision

C - relative sensitivity of the human eye, photopic vision

(After Blum[60])

$$I = I_o e^{-m\ (\alpha,\ s)} \qquad (21)$$

where $m(\alpha, s)$ is a function called the attenuation coefficient, which contains an absorption function, α, and a scattering function, s. The functions α and s are mutually dependent, but vary to different extents with the optical character of the medium and with the wavelength.

Effects of Ultraviolet Light on the Skin

The absorption of light by the skin is of interest to the designer of optical skin sensors as well as to those interested in ultraviolet effects.

Figure 2-78 represents the spectral absorption of light by white (W) and negro (N) skin.

Representation of the skin structures is diagrammatic, giving a schematized conception in which the dimensions should not be taken as generally representative, since the skin may vary widely in its thickness: c - corneum (horny layer of epidermis), m - Malpighian layer of epidermis, sw. - sweat gland, seb. - sebaceous gland, p - the most superficial blood vessels, arterioles, capillaries, and venules, h - hair follicle, s - hair shaft. The curves w and n give only rough estimates of depths at which

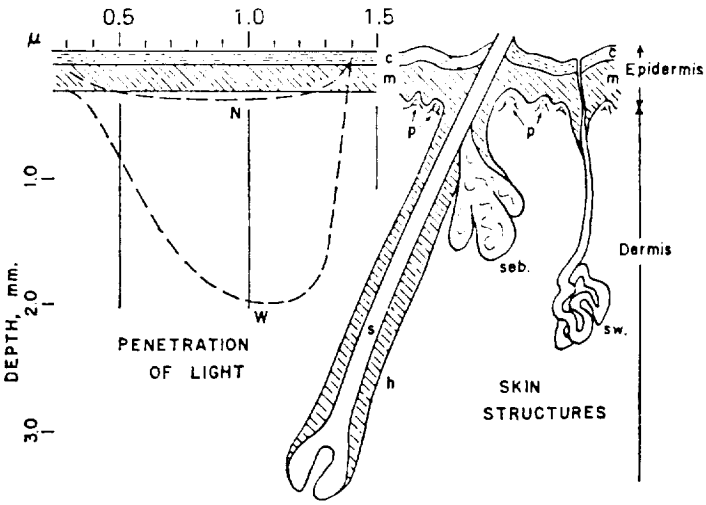


Figure 2-78

Penetration of Skin by Light

(After Blum[55])

radiation of the corresponding wavelengths is reduced to 5 percent of its incident value. There are insufficient data to make more than rough estimates, and these curves should be regarded as suggestive only.

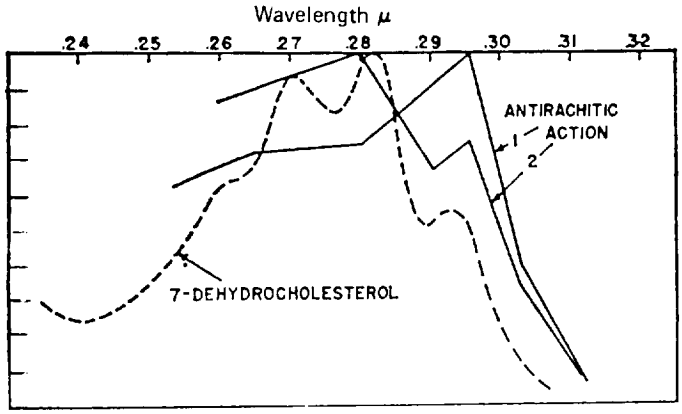
The penetration of ultraviolet rays of wavelengths shorter than 0.32 μ into the skin is of particular interest since these wavelengths produce specific physiologic and pathologic effects, the most obvious of which is sunburn. The thickness of the corneum varies widely from part to part of the body, and the depth of penetration of rays of these wavelengths varies accordingly. On the palms of the hands and soles of the feet, where this layer is very thick, virtually all of this radiation is absorbed before reaching the Malpighian layer. On the other parts of the body, the thickness may depend largely upon previous exposure to ultraviolet rays. Figure 2-79a shows the antirachitic (Rickets-preventing) action spectrum in two independent rat studies and the absorption spectrum of pro-vitamin D for conversion to active vitamin D in the skin. Figure 2-79b shows the erythema (redness) spectrum for the skin and absorption by the corneum which has a maximum near 0.28 μ corresponding to an absorption maximum for protein, a large component of this layer.

The fraction of radiation which has passed through the corneum is largely absorbed by the cells of the Malpighian layer by such strongly absorbing substances as proteins and nucleic acids. Here, scattering is probably considerably less, the optical boundaries being much less sharp than in the corneum. In general, very little radiation of wave lengths shorter than 0.32 μ penetrates deeper than the epidermis, but a small fraction may reach the papillary layer of the dermis and have its effect there. Another absorbing component of the epidermis needs particular mention, the melanin pigment, which gives the brown and black color to skin. This is a finely granular substance found in skin, hair, and some other organs of mammals. There is a good deal of variety in chemical composition. From its chemical composition, melanin may be expected to show a maximum of absorption at about the same position as that of protein, at 0.28 μ ; but, since the former is present in a much smaller amount in the corneum than the latter, its contribution to total absorption might be expected to be small. Melanin is a good scattering agent, however, and

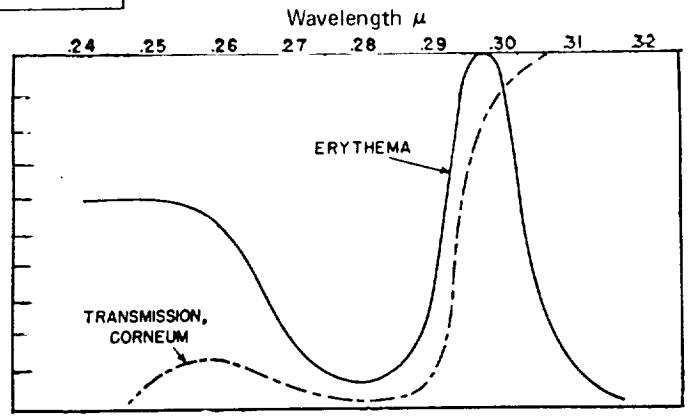
Figure 2-79

Biological Action Spectrum of Ultraviolet Light

(After Blum[58])



a. Antirachitic Spectra (Rat Studies 1 and 2) and Absorption Spectrum of Provitamin D (7-dehydrocholesterol). The Ordinates are in Arbitrary Action and Absorption Units on a Linear Scale from 0 to 1.0.



b. Erythemal Spectrum for Human Skin; Spectral Transmission of a Sample of Human Corneum. The Ordinates are in Arbitrary Action and Absorption Units on a Linear Scales from 0 to 1.0. Transmission of the Corneum is in Percent Extending Linearly from 0 to 25%.

may increase the absorption path. The quantitative role of melanin in protecting the skin against ultraviolet light is difficult to assess.

Transmission by the epidermis increases sharply for wavelengths longer than 0.32 μ ; the light penetration into the skin as a whole increases to a maximum in the near infrared around 1.0 μ , then falls to virtual extinction at about 1.4 μ due to strong absorption by water. Absorption by carotenoids and by hemoglobin in the long ultraviolet and shorter wavelengths of the visible can be neglected. Both these substances are important factors in determining the color or complexion of white skins, but have a minor effect on the total penetration of sunlight.

Sunburn

Exposure of skin to ultraviolet light results in the sunburn complex (56). Exposure of the skin to bright summer sunlight for half an hour or longer is followed, after a latent period of 3 to 6 hours, by dilatation of the minute vessels of the exposed area, manifested grossly as erythema (57, 216, 333). The erythema is accompanied by swelling, often so slight as to be almost imperceptible. If the exposure is prolonged, marked edema (swelling), desquamation (peeling), or blistering may follow, and there may be pain or

itching. The erythema fades in the course of a few days, being gradually replaced by "suntan" due to a rearrangement and increase of melanin in the epidermis. The suntan may persist for months or even years. In addition the suntan may darken by a process beginning almost immediately upon exposure, and ceasing with the exposure. The long latent period between exposure and the physiological responses may be accounted for by assuming that the physiologically active substances are elaborated by the injured cells at relatively slow rates.

Figure 2-79 shows an action spectrum for the erythema of sunburn of human skin obtained by determining, for a range of wavelengths, the dose of radiation required to elicit a just perceptible reddening. Numerous factors contribute to the complexity of the erythema response, and each may have somewhat different action spectra. This would help to explain the apparent paradox that reciprocity (dose-rate x time = constant) holds very well when erythema production is studied with monochromatic radiation, whereas with polychromatic radiation this is not the case (62). The erythema spectrum has sometimes been used as a standard for comparison of the action of sunlight with the action of artificial sources; but it is clear that with these complicating factors there may be considerable inaccuracy involved.

Thickening of Skin

A result of the action of ultraviolet radiation on the epidermis is a rapid proliferation of the cells of the Malpighian layer. This leads to thickening of that layer and also of the corneum, as many of the Malpighian cells die and are incorporated into the horny layer (60). Thickening of the corneum results in a marked decrease in the amount of sunburn-producing radiation that reaches the Malpighian layer; that is, the effectiveness of the corneum as a filter is increased, with a resultant reduction in sensitivity to sunburn. In white-skinned people, the thickening of the corneum is clearly a principal cause of the apparent immunity to sunburn that is experienced after exposure to sunlight or other source of ultraviolet radiation. This point is not generally understood, and it is commonly thought that the tanning of the skin, that is, the production of melanin pigment in the epidermis, is the only thing that gives protection from sunburn.

Tanning

The tanning process is itself quite complicated. In white races the melanin pigment, which confers the tan color, is found principally in the deepest part of the Malpighian layer (60, 62, 214, 215). About twenty hours after the exposure to ultraviolet light, some of this melanin begins to migrate toward the surface, and following this there is production of new pigment in the basal layer. Later, with the death of cells from the Malpighian layer and their incorporation into the corneum, the melanin gets into that layer too. In Negro skin the melanin is present in greater quantity and is also distributed more uniformly through the epidermis, including the corneum. Negro skin not only contains more melanin but also is thicker (411), both factors apparently contributing to the greater opacity that is associated with low susceptibility to sunburn (60). Ultimately, if the skin is not exposed, the melanin not only bleaches but also may disappear completely; but the

disappearance may take months or even years, whereas susceptibility to sunburn will have returned in several weeks.

Photoxicity and Photallergy

Certain drugs and disease states increase the sensitivity of the skin to long wave ultraviolet and even visible light. Several excellent reviews are available (18, 59).

Effects of Ultraviolet on the Eye

Light reaches a much greater depth in the eye (2.3 cm) than in any other part of the body. The media of the various parts of the eye, including the retina, are highly transparent to the wavelengths of visible light (approximately 0.39μ to 0.65μ), with little absorption and scattering (63). At the short end of the visible spectrum, however, about 50% of the light is scattered (101). Absorption of all wavelengths is virtually complete in the retinal pigment layer. There is no horny layer, as in the skin. The outer layer of the eye, the cornea, is a membrane consisting of extracellular collagen and polysaccharide. A thin layer of viable cells is kept moist by secretion from the lacrimal glands. Some attenuation of ultraviolet of greater than 0.32μ wavelength takes place in the lens. Wavelengths shorter than 0.32 μ, on the other hand, penetrate very little, apparently not reaching the lens to any great extent. As in the case of skin, water absorption sets the long wavelength limit at about 1.4μ . A diagram of the estimated spectral intensity of sunlight reaching the level of the retina is shown in Figure 2-80. Fluorescence

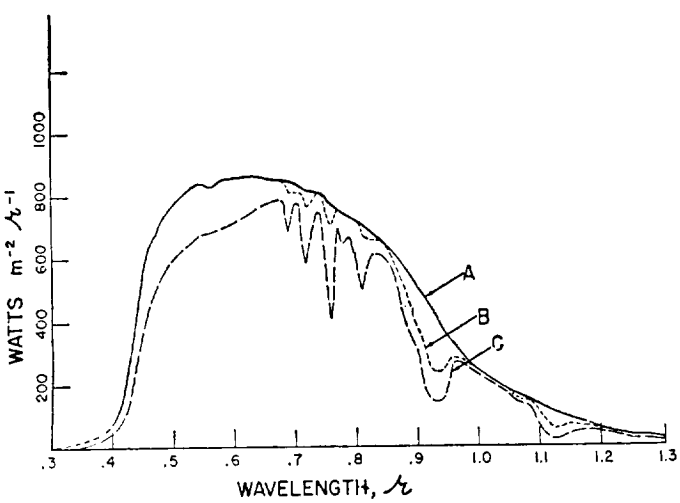


Figure 2-80

Estimates of Sunlight Reaching the Human Retina. A - Sun at Zenith, Dry Air; B and C - Air Containing 20 mm. Precipitable Water; B, Sun at Zenith, and C, Sun 60° from Zenith.

(After Blum[56])

of the optical media by ultraviolet light of about .36μ can degrade vision by decreasing contrast conditions through a glare effect.

Wavelengths shorter than 0.32μ that cause sunburn are absorbed very superficially in the eye, where they may cause damage to the cells of the cornea, called keratitis. The manifest symptoms are pain, disturbances of vision, and photophobia (light intolerance), with congestion of the conjunctiva, excessive secretion, and swelling, according to the extent of the injury. When

such symptoms occur after exposure in the neighborhood of snow fields, where there is a good deal of diffuse reflection, the condition is often referred to as "snow blindness". These wavelengths are absorbed so superficially that they do not cause damage to structures at any depth. Arc welders also get keratitis from UV emission in the arc (395).

The spectral dependence of energy required for threshold keratitic damage has not been determined for humans but is known for rabbits (102). The data are probably valid for humans.

The most characteristic sign of keratitis with threshold reactions is a stippled appearance within the corneal surface epithelium as seen by trans-illumination with the slit lamp and after staining with fluorescein. This stippling may be seen to be due to multiple punctate erosions (101). With more severe reactions there is a corresponding increase in the number of granules, ultimately forming a mosaic. With relatively severe exposures the cornea becomes uniformly hazy. It is of interest that the cloudiness of the stroma occurs only with amounts of radiation which would be expected on the basis of transmission measurements to penetrate the cornea in sufficient quantities to produce a threshold reaction in the endothelium or inner lining layer.

Figure 2-81 represents the action spectrum of keratitis and the absorption spectrum of several glasses 2 mm in thickness.

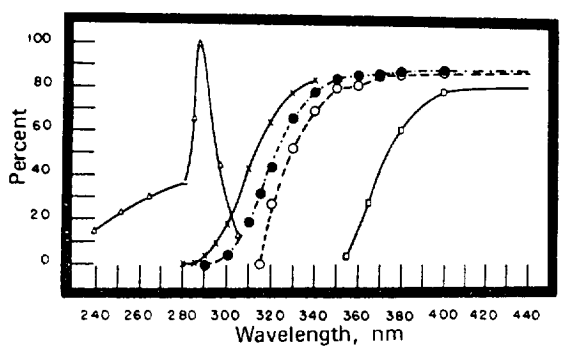


Figure 2-81

Curves Illustrating the Action Spectrum (Rabbits) of Keratitis (Line and Triangles) and the Absorption by Glass of 2 mm. Thickness of the Following Types: Crown or Spectacle Glass (Line and Crosses), Window Glass (Line and Dark Circles), Plate Glass (Line and Hollow Circles), and Flint Glass (Line and Rectangles).

(After Cogan and Kinsey[102])

The action spectrum rises abruptly with a peak of 288 nm, and shows by extrapolation that the long wavelength limit lies somewhere between 306 and 326 nm. The absorption curve of corneal epithelium peaks at 265 nm. There is no evidence of selective absorption at the wavelength corresponding to the peak of the action spectrum causing keratitis. This suggests that the amount of photosensitive substance present is small, e.g., an enzyme, or alternatively, that the abiotic effects are due to absorption by some small fraction of the protein complex having absorption maximums similar to the keratitis maximum. The energy necessary to elicit a threshold reaction in the cornea at the wavelength of peak sensitivity is of the order of 0.15×10^6 ergs. This is to be compared with the value of 2.0×10^6 ergs when the whole ultraviolet portion of the spectrum is utilized (102, 125, 426).

The lens does absorb some of the longer wavelengths of the ultraviolet. When the lens is removed these reach the retina where they stimulate the rods; the eye thus perceiving shorter wavelengths more than normally (431).

Retinal blindness caused by looking directly at the sun is not produced by ultraviolet but by focusing of light in the visible spectrum on the retinal structures (See Section A - Visible Light). Claims that ultraviolet rays may damage the retina seem unfounded. It is doubtful that either the ultraviolet or the total energy from sunlight can cause cataract in human eyes, that is, opacification of the lens. This may be brought about, however, by radiation from lower temperature sources, such as glass blowers' furnaces (glass blowers' cataract), which may have much more emission in the infrared than does sunlight (60).

Eye Protection Against Ultraviolet

The absorption of ultraviolet by optical media follows Lambert's Law of Equation 2-20. Part of the incident radiation is reflected at the front surface; part of it is absorbed in passing through the substance; and part is reflected at the back surface. In the case of glass about 4 percent of the radiation is reflected at each glass air surface when the radiation is incident normal to the surface. Another 4 percent is reflected at the surface where the light emerges, so that even if the glass had no absorption (and consequently 100 percent internal transmittance),its external transmittance would only be 92 percent.

A convenient way of presenting information about the internal transmittance of substances, I/I_o, is to give the values of the absorption coefficient at various wavelengths. Knowing this, the transmittance for any particular thickness may be calculated from Equation 2-20. For convenience in calculating, this relation is given graphically in Figure 2-82a where values of transmittance are plotted as a function of α with the thickness of the absorbing medium as a parameter. Figure 2-82b shows the values of transmittance as a function of the thickness of the medium with absorption coefficient as a parameter.

Data are available on the absorption coefficient of many different glasses and plastics (250). The transmission of glass in the ultraviolet is determined largely by the iron oxide content (ferric state) which absorbs strongly in this region. Impurities of less than 0.01 percent may have profound effects. Figure 2-81 indicates the absorption characteristics of the common glasses. A 2mm. thickness of crown glass reduces the exposure hazard approximately fifteenfold at 305 millimicrons, forty-five fold at 297 millimicrons and a hundred fold at 268 millimicrons (320). A 2 mm. thickness of flint glass affords essentially complete protection at all wavelengths. Pyrex and Corex, heat resistant glasses, have higher transmissions than plate or flint glasses. Vycor glasses, approaching silica in their properties, show very high transmission in the ultraviolet. These have been used for windows in the Mercury series (165). Fused quartz can be used where optimum ultraviolet transmission is required. Various glasses, crystalline minerals, and solutions can be used as filters for specific ultraviolet bands (250). Exposure to sunlight will gradually oxidize the absorbing minerals and increase the absorption of UV in glasses and plastics. This solarization must be accounted for when precise control of the ultraviolet transmission is required. Noviol glasses can be used in eye-protective devices where

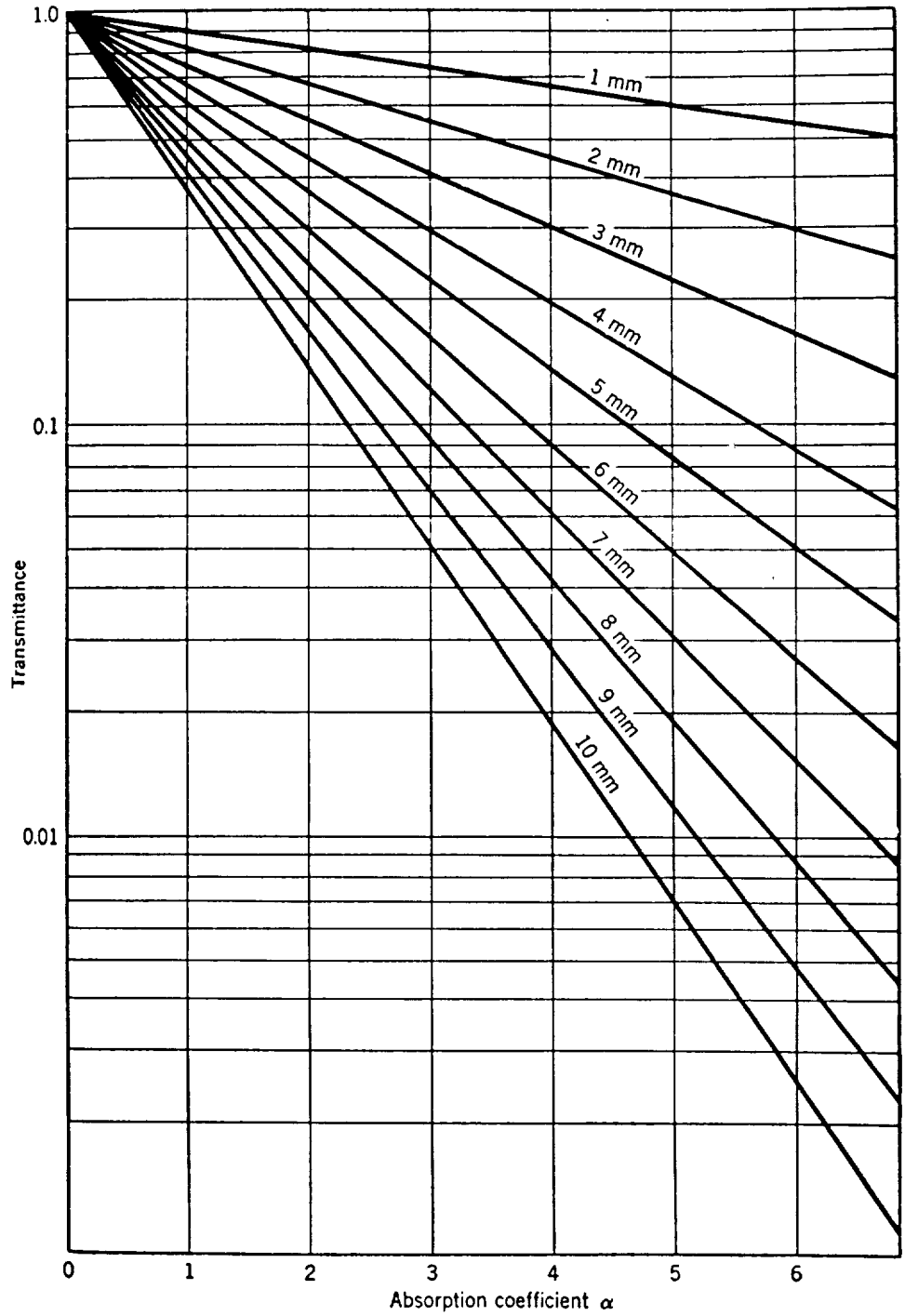


Figure 2-82a

Transmittance as a Function of Absorption Coefficient for Various Thicknesses of Absorbing Medium

(After Koller[250])

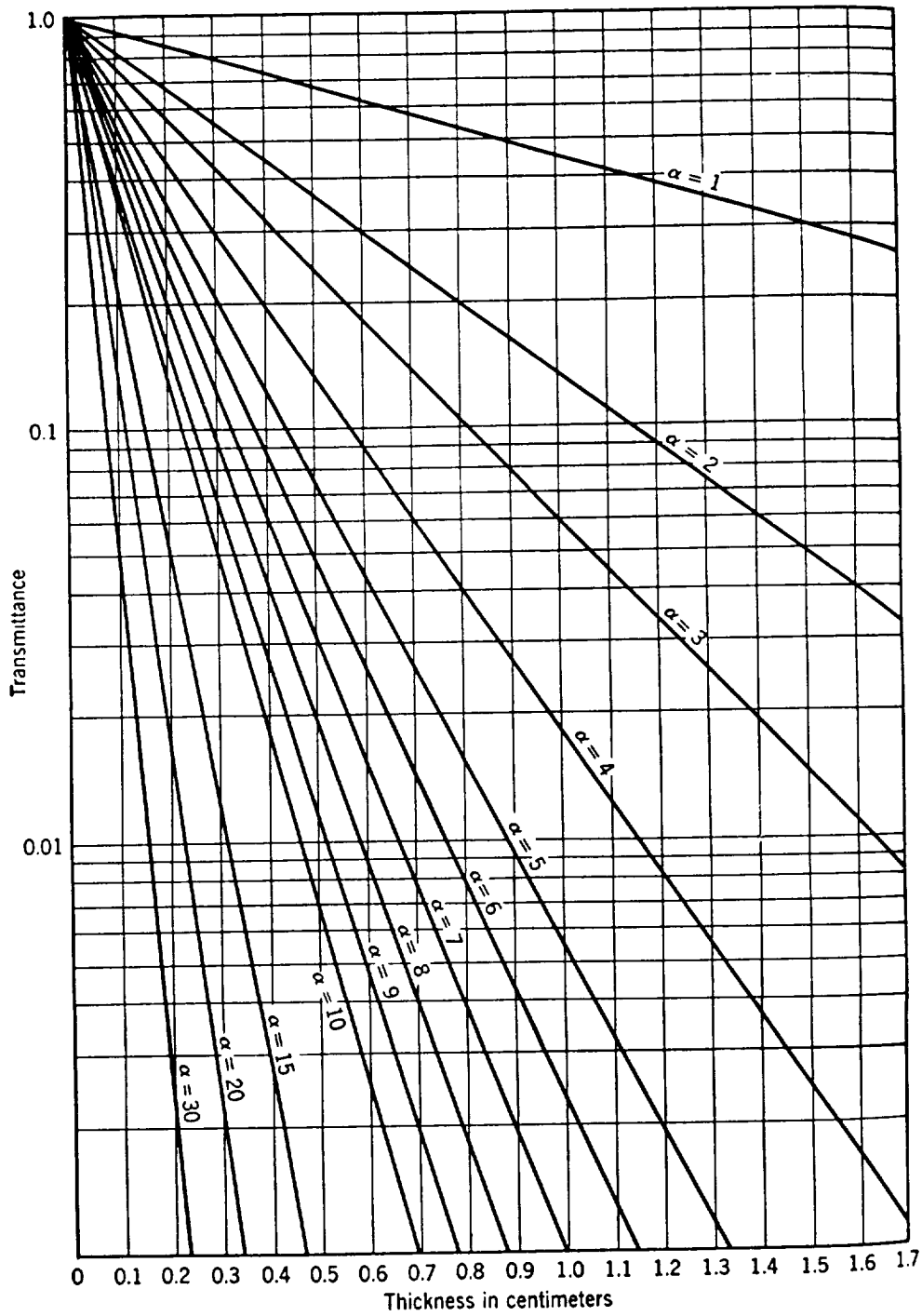


Figure 2-82b

Transmittance as a Function of Thickness for Various Values of Absorption Coefficient

(After Koller[250])

high intensity ultraviolet exposure is anticipated such as in welding (250, 395). Polaroid ultraviolet filters are also available (395).

Plastic materials vary in their absorption of ultraviolet (250, 395). Care must be taken in choosing the appropriate plastic window and visor materials maximizing UV absorption. Helmet polycarbonates do require UV inhibitors. Figure 2-83 presents the UV absorbance of four compounds used in plastics to increase the natural UV absorbance. In addition to absorbing ultraviolet light from the visual pathway, these compounds also stabilize the plastics by decreasing photo-oxidation and degradation of structural integrity. These compounds do tend to discolor the plastics to a variable degree. This factor must be controlled in helmet and visor applications (176).

In orbit or on the lunar or planetary surface, the full intensity of ultraviolet radiation is experienced (see solid line in Figure 2-77). Data are available on the ultraviolet transmission of military helmet visor systems (82, 87). For the gold-coated visor (Class 3) there is less than 0.5% for any wavelength in the 290 to 320 nm erythemal band. Such visor systems can absorb the visible light band to a 2% transmission level and cause no operational problems except in dusk light conditions (87).

Eye Trauma in Space Operations

Weightlessness in orbit increases the chances of trauma to the eye by floating debris and chemicals. Treatment of the various eye trauma syndromes in space operations has been covered in great detail in a recent review (84).

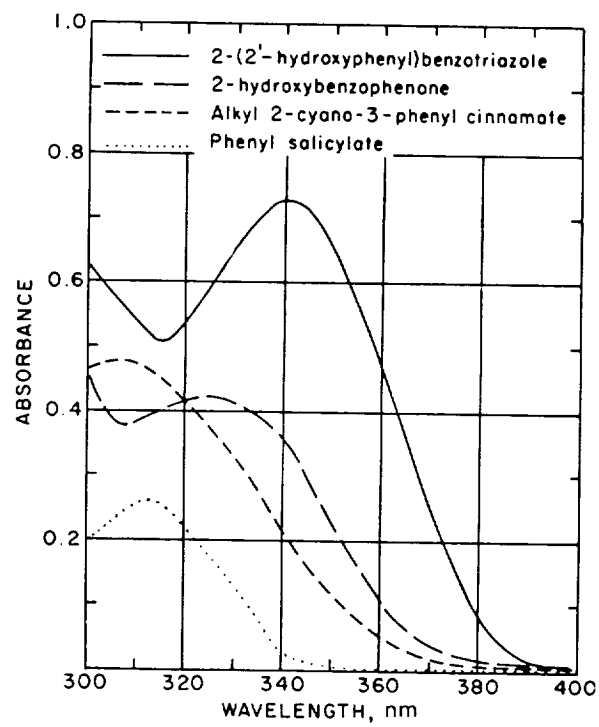


Figure 2-83
Variations in UV Absorbance of the Four Compounds Most Commonly used as UV Absorbers in Plastics

Wavelength range shown is that most important in protection of plastics against photodegradation. Absorbers were at a concentration of 1.0 mg/100 ml in $CHCl_3$

(After Gordon and Rothstein[176])

REFERENCES

2-1. Adler, F. H., Physiology of the Eye: Clinical Application, C. V. Mosby Co., St. Louis, 3rd Edition, 1959.

2-2. Advisory Group for Aerospace Research and Development, Loss of Vision from High Intensity Light, AGARD-CP-11, 1966, A Symposium sponsored by the Aerospace Medical Panel of AGARD-NATO, Paris, France, Mar. 16-17, 1966. (AD-653917).

2-3. Aeronautical Systems Division, Colors, Aeronautical Lights and Lighting Equipment, General Requirements for #ASG#, MIL-C-25050A, Research and Technology Div., Systems Engineering Group, Wright-Patterson AFB Ohio, Dec. 2, 1963.

2-4. Air Force, Washington, D. C., Lenses, Goggle and Visor, Helmet, Optical Characteristics, General Specification. MIL-L-38169, Mar. 26, 1963 and Amend. 2, Sept. 21, 1964.

2-5. Air Force Systems Command Headquarters, Handbook of Instructions for Aerospace Personnel Subsystem Designers (HIAPSD), AFSCM-80-3, Washington, D. C., 1966.

2-6. Aitken, R. C., Ferres, H. M., Gedye, J. L., Distraction from Flashing Lights, Aerospace Med., 34: 302-306, Apr. 1963.

2-7. Akulinichev, I. T., Yemel'yanov, M. D., Maksimov, D. B., Oculomotor Activity in Cosmonauts during Orbital Flight, Izvestia Akademiia Nauk SSSR, Seria Biologicheskaia, No. 2: 274-278, Mar. Apr., 1965.

2-8. Alexander, W. C., Sever, R. J., Fedderson, W. E., et al., Acceleration ($+G_x$) Induced Hypoxemia and Crew Performance, NASA Manned Spacecraft Center, Houston, Texas. Paper presented at the Scientific Program, Aerospace Med. Assn., 35th Annual Mtg., May 11-14, 1964, Miami Beach, Fla.

2-9. Allen, L. K., Dallenbach, K. M., The Effect of Light Flashes during the Course of Dark Adaptation, Amer. J. Psychol., 51: 540-548, 1938.

2-10. Allen, R. G., Jungbauer, D. E., Isgitt, D. J., et al., Nuclear Flash Eye Effects Technical Report for Military Planners, School of Aerospace Medicine, Aerospace Medical Div., Brooks AFB, Texas, Feb. 1967. (AD-659145).

2-11. Allen, R. W., Hershberger, M. L., Telescope Field-of-View Requirements for Star Recognition, Human Factors, 8: 41-47, 1966.

2-12. Allen, W. H., Need for Validity in Simulation of the Extra-terrestrial Visual Environment, AIAA-67-251, presented at AIAA Flight Test, Simulation and Support Conference, Cocoa Beach, Fla., Feb. 6-8, 1967.

2-13. Allphin, W., BCD Appraisals of Luminaire Brightness in a Simulated Office, Illum. Engin. 56: 31, 1961.

2-14. Arden, G. B., The Sensory Effects of Drugs, Electrophysiological Investigations of the Mechanism of the Action of Drugs on the Eye, in Recent Developments in Vision Research, Whitcomb, M. A., (ed.), NAS-NRC-1272, National Academy of Sciences - National Research Council, Washington, D. C., 1966, pp. 194-209.

2-15. Argyle, E., Optical Environment in Gemini Space Flights, Science, 155(3760): 354, Jan. 1967.

2-16. Arnold Engineering Development Center, Annual Symposium on Space Environment Simulation, Fifth, May 21-22, 1964, AEDC, Headquarters, Arnold Air Force Station, Tenn., 1965. (AD-441312).

2-17. Aulhorn, E., Uber Die Sehscharfe Bei Herabgesetzter Beleuchtung, Ber. Deutsch. Ophth. Ges., 64: 555-559, 1961.

2-18. Baer, R. L., Harber, L. C., Light Sensitivity in Biologic Systems, Phototoxicity and Photoallergy Related to Visible Light, Fed. Proc., 24: S-15-S-21, 1965.

2-19. Baird, F. E., Schindler, R. A., Smith, R. N., An Optical Aid for Manual Acquisition and Tracking of a Target Satellite during a Rendezvous Mission, Adv. Astronautical Sci., 16: 585-598, 1963.

2-20. Baird, J. C., Effects of Stimulus-Numerosity upon Distance Estimates, Psychon. Sci., 6(4): 133-134, 1966.

2-21. Baird, J. C., Biersdorf, W. R., Quantitative Functions for Size and Distance Judgments, Percept. Psychophysics, 2: 161-166, 1967.

2-22. Baker, C. A., Steedman, W. C., Estimation of Visually Perceived Closure Rates, Human Factors, 4: 343-347, Dec. 1962.

2-23. Baker, C. A., Steedman, W. C., Perceived Movement in Depth as a Function of Luminance and Velocity, Human Factors, 3(3): 166-173, Sept. 1961.

2-24. Baker, C. A., Morris, D. F., Steedman, W. C., Target Recognition on Complex Displays, WADC-TR-59-418, 1959.

2-25. Baker, C. A., Grether, W. F., Visual Presentation of Information, WADC-TR-54-160, Wright Air Dev. Center, Wright-Patterson AFB, Ohio, 1954.

2-26. Baker, K. E., Some Variables Influencing Vernier Acuity. I. Illumination and Exposure Time. II. Wavelength of Illumination, J. Opt. Soc. Amer., 39: 567-576, 1949.

2-27. Barber, E., Radiometry and Photometry of the Moon and Planets, JPLAI-LS-345, Jet Propulsion Lab., California Inst. of Technology, Pasadena, Calif., Sep. 1961.

2-28. Bartley, S. H., Light Adaptation and Brightness Enhancement, Percept. Motor Skills, 7: 85-92, 1957.

2-29. Bartley, S. H., The Psychophysiology of Vision, in Handbook of Experimental Psychology, Stevens, S. S. (ed.), John Wiley & Sons, Inc., N. Y., 1951, Chapt. 24.

2-30. Bartley, S. H., Vision: A Study of Its Basis, Hafner Publishing Co., N. Y., 1963, p. 239.

2-31. Bate, A. J., Bates, C., Jr., A Comparison of Cockpit Warning Systems, AMRL-TR-66-180, Aerospace Medical Research Labs., Wright-Patterson AFB, Ohio, Apr. 1967.

2-32. Bate, A. J., Self, H. C., Target Detection on Side-Looking Radar When Image Motion Can be Temporarily Delayed, AMRL-TR-67-23, Aerospace Medical Research Labs., Wright-Patterson AFB, Ohio, Nov. 1967.

2-33. Beasley, G. P., Pilot-Controlled Simulation of Rendezvous between a Spacecraft and a Command Module Having Low Thrust, NASA-TN-D-1613, 1963.

2-34. Bergey, G. E., Sipple, W. C., Hamilton, W. A., et al., A Technique for Determining an Index of Visual Alertness from the Electroencephalogram, NADC-MR-6618, Naval Air Development Center, Aerospace Medical Research Department, Johnsville, Pa., May 1967.

2-35. Berry, C. A., Eastwood, H. K., Helicopter Problems: Noise, Cockpit Contamination and Disorientation, Aerospace Med., 31: 179-190, Mar. 1960.

2-57. Blum, H. F., Terus, W. S., Inhibition of the Erythema of Sunburn by Large Doses of Ultraviolet Radiation, Amer. J. Physiol., 146: 97-106, 1946.

2-58. Blum, H. F., Photobiological Research with Particular Reference to Skin, J. A. M. A., 173: 1353, 1357, 1960.

2-59. Blum, H. F., Photodynamic Action and Diseases Caused by Light, Hafner Publishing Co., N. Y., Revised Edition, 1964.

2-60. Blum, H. F., Physiological Effects of Sunlight on Man, Physiol. Rev., 25: 483-530, 1945.

2-61. Blum, H. F., Solar Energy Reaching the Retina: Proposed Spectral Curve for Testing Sunscanning Glasses, Research Proj. X 435, Nav. Med. Res. Inst., Bethesda, Md., 1944.

2-62. Blum, H. F., Sunburn, in Radiation Biology, Vol. II, Ultraviolet and Related Radiations, Hollaender, A., McGraw-Hill, N. Y., 1955, pp. 487-528.

2-63. Boettner, E. A., Spectral Transmission of the Eye, Univ. of Michigan, Contract AF41(609)-2966, School of Aerospace Medicine, Brooks AFB, Texas, Jul. 1967.

2-64. Boring, E. G., Langfeld, H. S., Weld, H. P., Foundations of Psychology, John Wiley & Sons, N. Y., 1948.

2-65. Breckenridge, F. C., Colors of Signal Lights, Their Selection, Definition, Measurement, Production, and Use, NBS-Monograph-75, National Bureau of Standards, Washington, D. C., Apr. 1967.

2-66. Breinin, G. M., Perryman, J. H., Studies in the Pharmacology of Extraocular Muscles, in Recent Developments in Vision Research, Whitcomb, M. A., (ed.), NAS-NRC-1272, National Academy of Sciences - National Research Council, Washington, D. C., 1966, pp. 210-212.

2-67. Brissenden, R. F., Burton, B. B., Foudriat, E. C., et al., Analog Simulation of a Pilot-Controlled Rendezvous, NASA-TN-D-747, 1961.

2-68. Brissenden, R. F., A Study of Human Pilot's Ability to Detect Angular Motion with Application to Control of Space Rendezvous. NASA-TN-D-1498, Dec. 1962.

2-69. Brissenden, R. F., Lineberry, E. C., Jr., Visual Control of Rendezvous. Aerospace Engr., 21: 64-65, 74-78, June 1962.

2-70. Britten, A. J., Eye-Protective Devices, Ordnance, 45: 312-315, Nov.-Dec. 1964.

2-71. Broadbent, D. E., On the Dangers of Over-Arousal, MRC Applied Psychology Unit, Cambridge, England. Paper presented at the Basic Environmental Problems of Man in Space, 2nd International Symposium, Paris, June 14-18, 1965.

2-72. Broadbent, D. E., Vigilance, Brit. Med. Bull., 20(1): 17-20, 1964.

2-73. Brown, D. R. E., Natural Illumination Charts, U. S. Navy R & D Project NS 714-100, Report No. 374-1, Sept. 1952.

2-74. Brown, F. R., A Study of the Requirements for Letters, Numbers, and Markings to be Used on Trans-Illuminated Aircraft Control Panels. Part 4, Legibility of Uniform Stroke Capital Letters as Determined by Size and Height to Width Ratio and as Compared to Garamond Bold, Proj. TED NAM EL-609, Naval Air Material Center, Aeronautical Med. Equip. Lab., Philadelphia, Pa., March 10, 1953.

2-75. Brown, J. L., Experimental Investigations of Flash Blindness, Human Factors, 6: 503-516, 1964.

2-76. Brown, J. L., Study of Visual Perception in Humans and Animals, Sensitivity and Spectral Response Properties of Human Vision at Low Luminances, Tech. Rep. 2, Kansas State University, Manhattan, Kan., 1966. (AD-640555).

2-77. Brown, J. L., Phares, L., Fletcher, D. E., Spectral Sensitivity of the Eye Based on Visual Acuity, NADC-MA-6006, Naval Air Dev. Center, Johnsville, Pa., Apr. 1960.

2-78. Brown, R. H., Visual Sensitivity to Differences in Velocity, Psychol. Bull., 58: 89-103, Mar. 1961.

2-79. Brown, R. H., Weber Ratio for Visual Discrimination of Velocity, Science, 131: 1809-1810, Mar. 7, 1960.

2-80. Bryam, G. M., The Physical and Photochemical Basis of Visual Resolving Power. I. The Distribution of Illumination in Retinal Images, J. Opt. Soc. Amer., 34: 571-591, 1944.

2-81 Buckner, D. N., McGrath, J. J., Vigilance: A Symposium, McGraw-Hill, N. Y., 1963.

2-82. Bureau of Naval Weapons, Visors, Protective, Helmet, MIL-V-22272B (WP), Military Specifications, Washington, D. C., Jan. 28, 1965.

2-83. Burg, J., Visual Acuity as Measured by Dynamic and Static Tests: A Comparative Evaluation, J. Appl. Psychol., 50(6): 460-466, 1966.

2-84. Busby, D. E., Clinical Space Medicine: A Prospective Look at Medical Problems from Hazards of Space Operations, NASA-CR-856, 1967.

2-85. Cameron, W. S., Man in Space, in Introduction to Space Science, Ness, W. N., (ed.), Gordon and Breach, N. Y., 1965, p. 545.

2-86. Carel, W. L., Visual Factors in the Contact Analog, GE-R61ELC60, General Electric, Ithaca, N. Y., 1961.

2-87. Carpenter, J. A., Richey, E. O., Evaluation of Two Percent Gold Visor, SAM-TR-66-71, School of Aerospace Medicine, Brooks AFB, Texas, 1966.

2-88. Catterson, A. D., NASA, Manned Spacecraft Center, Houston, Texas, personal communication, 1967.

2-89. Cavonius, C. R., The Effect of Wavelength on Visual Acuity, ERF-RR-1/67-Cr, The Eye Research Foundation, Bethesda, Md., 1967. (AD-646575).

2-90. Chalmers, E. L., Goldstein, M., Kappauf, W. E., The Effect of Illumination on Dial Reading, AF-TR-6021, Wright-Patterson AFB, Ohio, 1950.

2-91. Chapanis, A., Garner, W. R., Morgan, C. T., Applied Experimental Psychology, John Wiley & Sons, N. Y., 1949.

2-92. Chapanis, A., Color Names for Color Space, Amer. Sci., 53: 327-346, Sept. 1965. (AD-626313).

2-93. Chapanis, A., How We See: A Summary of Basic Principles, in Human Factors in Undersea Warfare, National Research Council, Washington, D. C., 1949, pp. 3-60.

2-94. Chisum, G. T., Trent, K. B., Morway, P. E., Effects of Blue Cutoff Filters on Color Discrimination, NADC-MR-6704, Naval Air Development Center, Aerospace Medical Res. Dept., Johnsville, Warminster, Pa., Apr. 1967.

2-95. Chisum, G. T., Intraocular Effects on Flashblindness, NADC-MR-6719, Naval Air Development Center, Aerospace Medical Res. Dept., Johnsville, Warminster, Pa., Dec., 1967.

2-96. Clark, H. J., Control of a Remote Maneuvering Unit Satellite Inspection, AMRL-TR-66-134, Aerospace Medical Research Labs., Wright-Patterson AFB, Ohio, 1966.

2-97. Clark, H. J., Optimum Angular Accelerations for Control of a Remote Maneuvering Unit, AMRL-TR-66-20, Aerospace Medical Research Labs., Wright-Patterson AFB, Ohio, Mar. 1966.

2-98. Clark, H. J., Space Rendezvous Using Visual Cues Only, Human Factors, 7: 63-70, 1965. (Also published as: AMRL-TR-65-10, Aerospace Medical Res. Labs., Wright-Patterson AFB, Ohio).

2-99. Clark, W. B., Culver, J. F., Space Ophthalmological Problems, in Bioastronautics and the Exploration of Space, Proceedings of the Third International Symposium, San Antonio, Texas, Nov. 16-18, 1964, Bedwell, T. C., Jr., and Strughold, H., (eds.), pp. 149-155. (AD-627686).

2-100. Cobb, P. W., Moss, F. K., Four Fundamental Factors in Vision, Trans. Illum. Engng. Soc., 23: 496-506, 1928.

2-101. Cogan, D. G., Howe Laboratory of Ophthalmology, Harvard University Medical School, Massachusetts Eye and Ear Infirmary, Boston, Mass., personal communication, 1968.

2-102. Cogan, D. G., Kinsey, V. E., Action Spectrum of Keratitis Produced by Ultraviolet Radiation, Arch. Ophthal., 35: 670-677, 1946.

2-103. Colgan, C. M., The Effect of Observational Technique on Brightness-Enhancement, Amer. J. Psychol., 78: 471-475, 1965.

2-104. Conklin, J. E., Literature Review and Experimental Design for Research on Velocity Perception Related to Space Rendezvous Requirements, Interdepartmental Correspondence Ref. 2732.30/87, Hughes Aircraft Co., Culver City, Calif., May 8, 1962.

2-105. Conklin, J. E., Visual Requirements for Landing on the Moon, Human Factors, 4: 335-342, 1962.

2-106. Conover, D. W., Kraft, C. L., The Use of Color in Coding Displays, WADC-TR-55-471, Wright Air Dev. Center, Wright-Patterson AFB, Ohio, 1958. (AD-204214).

2-107. Conticelli, M., Training and Retinal Location Affecting the Periodic Fluctuation of Apparent Brightness during Prolonged Fixation, AFOSR-4195, Air Force Office of Scientific Research, Washington, D. C., 1962. (Reprinted from: Atti. Fond. G. Ronchi, 17: 396-404, July-Aug. 1962). (AD-637648).

2-108. Cook, G., Stark, L., The Human Eye-Movement Mechanism: Experiments, Modeling and Model Testing, SRL-67-0005, Frank J. Seiler Research Laboratory, U. S. Air Force Academy, Colo., June 1967. (AD-654626).

2-109. Crane, H. D., A Theoretical Analysis of the Visual Accommodation System in Humans, NASA-CR-606, 1966.

2-110. Crawford, B. H., Photochemical Laws and Visual Phenomena, Proc. Roy. Soc. London, 133B: 63-75, Jan. 1946.

2-111. Crawford, W. A., Visual Acuity and Moving Objects. III. The Coordination of Eye and Head Movements, FPRC Memo 150c, Institute of Aviation Medicine, Royal Air Force, Farnborough, England, July 1960.

2-112. Cronin, J. F., Adams, J. B., Colwell, R. N., A Proposed Multispectral Photography Experiment for AES Lunar Orbital Mission, AFCRL-66-796, Air Force Cambridge Research Labs., Hanscom Field, Bedford, Mass., 1966.

2-113. Crook, M. N., Coules, J., The Effect of Noise on the Perception of Forms in Electro-Visual Display Systems, Final Report, Contract DA-49-007-MD-536, Institute for Applied Experimental Psychology, Tufts University, Medford, Mass., Jan. 1959.

2-114. Crook, M. N., Coules, J., Reduced Contrast and Contour Degradation as Factors in Impairment of Form Discrimination, Interim Rep. 7, Contract DA-49-007-MD-536, Institute for Applied Experimental Psychology, Tufts University, Medford, Mass., Jan. 1959.

2-115. Crumley, L., Divany, R., Gates, S., Hostetter, R., et al., Display Problems in Aerospace Surveillance Systems, Part 1. A Survey of Display Hardware and Analysis of Relevant Psychological Variables, ESD-TR-61-33, Air Force Electronic Systems Div., L. G. Hanscom Field, Bedford, Mass., 1961.

2-116. Culver, J. F., Adler, A. V., Protective Glasses Against Atomic Flash, in Visual Problems in Aviation Medicine, Mercier, A., (ed.), Pergamon Press, N. Y., 1962, pp. 34-38.

2-117. Davson, H., (ed.), The Eye: Vol. I. Vegetative Physiology and Biochemistry, Vol. 2. The Visual Process, Vol. 3. Muscular Mechanisms, Vol. 4. Visual Optics and the Optical Space Sense, Academic Press, London, 1962.

2-118. De Mott, D. W., Davis, T. P., An Experimental Study of Retinal Burns: Part I. The Irradiance Thresholds for Chorio-Retinal Lesions. Part II. Entoptic Scatter as a Function of Wave Length, UR-548, University of Rochester, N. Y., May 1959. (Also in Arch. Ophthal., 62: 653-656, 1959).

2-119. Derksen, W., Griff, N., Glossary of Radiometric and Photometric Concepts Used in Retinal Burn and Flashblindness Research (Definitions, Symbols and Units), Progress Rep. 18, Naval Applied Science Lab., Brooklyn, N. Y., under DASA Subtask 03.001, Dec. 1967.

2-120. DeRocher, W. L., Jr., Wudell, A. E., Manual Tracking for a Space-to-Space Photographic Mission, Control Systems Research, Martin Co., Denver, Colo., Jan. 1966.

2-121. Deutsch, S., Human Factors Challenges in Manned Space Flight, SAE-Paper 650809, Society of Automotive Engineers, National Aeronautic and Space Engineering and Manufacturing Meeting, Los Angeles, Oct. 4-8, 1965.

2-122. Devoe, D. B., Duva, J. S., Display Sharing Through Color Filtering, ESD-TN-60-60, Air Force Electronic Systems Div., L. G. Hanscom Field, Bedford, Mass., 1960.

2-123. Dobbins, D. A., Ah Chu, R., Kindick, C. M., Jungle Vision VII: Seasonal Variations in Personnel Detectability in a Semi-deciduous Tropical Forest, Res. Rep. 8, Army Tropic Test Center, Fort Clayton, Canal Zone, Jan. 1967.

2-124. Doyle, C. D., Aftergut, S., Development of a Reversibly Frostible Transparency for a Nuclear Flash Eye Protection Shutter, General Electric, Schenectady, N. Y., 1966. (AD-642732).

2-125. Duke-Elder, W. S., Pathologic Action of Light upon the Eye; Photophthalmia, Lancet, 1: 1137-1140, June 1926.

2-126. Duke-Elder, W. S., System of Ophthalmology, C. V. Mosby Co., St. Louis, Vol. I, 1958, Vol. II, 1961.

2-127. Dunkelman, L., Mercer, R. D., Dim Light Photography and Visual Observations of Space Phenomena from Manned Spacecraft, NASA-TM-X-55752, Goddard Space Flight Center, Greenbelt, Maryland, Feb. 1966.

2-128. Dunkelman, L., Gill, J. R., McDivitt, J. A., et al., Geo-Astronomical Observations, in Manned Space Flight Experiments Symposium, Gemini Missions III and IV, NASA-TM-X-56861, 1965.

2-129. Dunlap and Associates, Inc., Darien, Conn., Man-Machine Relationships in Prelaunch Checkout of Advanced Space Vehicles, Final Summary Report, NASA-CR-69172, 1965.

2-130. Duntley, S. Q., Visibility Laboratory, Scripps Institute of Oceanography, University of California, San Diego, Calif., personal communication, 1966.

2-131. Duntley, S. Q., Austin, R. W., Taylor, J. H., et al., Experiment S-8/D-13, Visual Acuity and Astronaut Visibility, in Gemini Midprogram Conference Including Experiment Results, Part II, A, NASA-SP-121, 1966, pp. 329-346. (Also: S10-Ref-66-17, Scripps Institution of Oceanography, University of California, San Deigo, Calif., July 1966)

2-132. Duntley, S. Q., Gordon, J. I., Taylor, J. H., et al., Visibility, Appl. Opt., 3: 549-598, May 1964.

2-133. Duntley, S. Q., The Visibility of Distant Objects, J. Opt. Soc. Amer., 38(3): 237-249, Mar. 1948.

2-134. Duntley, S. Q., Visibility in the Oceans, Optical Spectra, 1(4): 64-69, Fourth Quarter 1967.

2-135. Eastman Kodak Co., Influence of Color Contrast on Visual Acuity, OSRD-4541, National Defense Research Committee; U. S. Office of Scientific Research and Development, 1944.

2-136. Eastman Kodak Co., Tech Bits, 1: 5, 1965.

2-137. Egan, J. P., Signal Detection Theory and Psychophysics: A Topical Bibliography, Indiana University Hearing and Communication Laboratory, for National Academy of Sciences - National Research Council Committee on Hearing, Bioacoustics, and Biomechanics, under Grant AF-AFOSR-548-67, Dec. 1967. (AD-663906).

2-138. Enoch, J. M., Fry, G. A., Visual Search of a Complex Display: A Summary Report, RADC-TN-59-65, Rome Air Development Center, Griffiss AFB, N. Y., 1958.

2-139. Epstein, W., Franklin, S., Some Conditions of the Effect of Relative Size on Perceived Relative Distance, Amer. J. Psychol., 78: 466-470, 1965.

2-140. Erickson, R. A., Relation between Visual Search Time and Peripheral Visual Acuity, Human Factors, 6: 165-177, Apr. 1964.

2-141. Erickson, R. A., Visual Detection of Targets: Analysis and Review, NOTS-TP-3645, Naval Ordnance Test Station, China Lake, Calif., 1965. (AD-612721).

2-142. Eysench, H. J., A Critical and Experimental Study of Color Preferences, Amer. J. Psychol., 54: 385-394, 1941.

2-143. Fender, D. H., Beeler, G. W., Jr., Human Eye Movements during Fixation, in A Report for the Year 1964-1965 of the Research and Other Activities, California Institute of Technology, Division of Engineering and Applied Science, Pasadena, Calif., 1965, p. 92.

2-144. Fenn, R. W., Correlation Between Atmospheric Backscattering and Meteorological Visual Range, AFCRL-66-549, Air Force Cambridge Research Labs., L. G. Hanscom Field, Bedford, Mass., 1966.

2-145. Ferree, C. E., Rand, G., Intensity of Light and Speed of Vision Studied with Special Reference to Industrial Situations, Part I., Trans. Illum. Engin. Soc., 22: 79-110, 1927.

2-146. Ferree, C. E., Rand, G., Visibility of Objects as Affected by Color and Composition of Light. Part II. With Lights Equalized in Both Brightness and Saturation, Person. J., 10: 108-124, 1931.

2-147. Fincham, E. F., The Accommodation Reflex and Its Stimulus, Brit. J. Ophthal., 35: 381-393, 1951.

2-148. Fitts, P. M., Engineering Psychology and Equipment Design, in Handbook of Experimental Psychology, Stevens, S. S., (ed.), John Wiley & Sons, Inc., N. Y., 1951.

2-149. Fiorentini, A., Ronchi, L., Problems Related to Visual Performance of Pilots, Istituto Nazionale di Ottica, Arcetri-Firenze, Italy, 1965. (AD-630475).

2-150. Forman, P. F., The Photographic Window, The Perkin-Elmer Corp., Electro-Optical Div., Norwalk, Conn., in New Developments for Aerial Photography, A Program of Talks Presented to Members of OSA, ASP, SPIE, and SPSE at a Joint Technical Meeting, Sept. 16, 1964.

2-151. Franklin, M. E., Whittenburg, J. A., Research on Visual Target Detection. Part I. Development of an Air-to-Ground Detection/Identification Model, HSR-RR-65/4-Dt, Human Sciences Research, Inc., McLean, Va., 1965. (AD-619275).

2-152. Fraser, T. M., The Intangibles of Habitability during Long Duration Space Missions, The Lovelace Foundation for Medical Education and Research, Albuquerque, N. M., Contract NASr-115, 1967. (In Press).

2-153. Frederickson, E. W., Follettie, J. F., Baldwin, R. D., Aircraft Detection, Range Estimation, and Auditory Tracking Tests in a Desert Environment, HUMRRO-TR-67-3, Human Resources Research Office, The George Washington Univ., Washington, D. C., Mar. 1967.

2-154. Fry, G. A., Alpern, M., Effects of Flashes of Light on Night Visual Acuity, WADC-TR-52-10, Pt. I., Wright Air Development Center, Wright-Patterson AFB, Ohio, Nov. 1951.

2-155. Fry, G. A., The Evaluation of Discomfort Glare, Illum. Engin., 51: 722-728, 1956.

2-156. Gauer, O. H., Zuidema, G. D., (eds.), Gravitational Stress in Aerospace Medicine, Little Brown, Boston, 1961.

2-157. Gerathewohl, S. J., Conspicuity of Flashing Light Signals: Effects of Variation Among Frequency, Duration and Contrast of the Signals, Project 21-1205-0012, Rep. No. 1, School of Aviation Med., Randolph Field, Texas, 1954.

2-158. Gerathewohl, S. J., Conspicuity of Flashing and Steady Light Signals, II. High Contrasts, Project 21-24-014, Rep. No. 2, School of Aviation Med., Randolph Field, Texas, 1952.

2-159. Gerathewohl, S. J., Eye Movements during Radar Operations, J. Aviat. Med., 23: 597-607, 1952.

2-160. Gerathewohl, S. J., Rubinstein, D. A., Investigation of Perceptual Factors Involved in the Interpretation of PPI-Scope Presentations, II. A Pilot Study on Form Discrimination, Project 21-24-009, Rep. No. 2, School of Aviation Med., Randolph Field, Texas, 1952.

2-161. Gibson, J. J., The Perception of the Visual World, Riverside Press, Cambridge, Mass., 1958.

2-162. Gibson, J. J., Report to the Office of Naval Research on Published Research Studies and Other Contributions between 1957 and 1967 Supported in Whole or Part under Contract No. NONR-401(14), Cornell Univ., Ithaca, N. Y., Apr. 1967. (AD-652392).

2-163. Gilchrist, J. D., Anderson, P. A., Research on Computational and Display Requirements for Human Control of Space Vehicle Boosters, Part I: Theory and Results, NASA-CR-89606, Aug. 1967.

2-164. Gillies, J. A., (ed.), A Textbook of Aviation Physiology, Pergamon Press, N. Y., 1965.

2-165. Goetzel, C. G., Rittenhouse, J. B., Singletary, J. B., (eds.), Space Materials Handbook, 2nd Edition, ML-TDR-64-40A, Air Force Materials Lab., Wright-Patterson AFB, Ohio, Jan. 1965.

2-166. Gogel, W. C., Mertens, H. W., Perceived Depth between Familiar Objects, FAA-AM-67-20, Federal Aviation Administration, Office of Aviation Medicine, Oklahoma City, Okla., Aug. 1967.

2-167. Gogel, W. C., The Perception of Depth from Binocular Disparity, FAA-CARI-63-10, Federal Aviation Agency, Oklahoma City, Okla., 1963.

2-168. Gogel, W. C., The Perception of Space with Binocular Disparity Cues, AMRL-379, Army Medical Res. Lab., Fort Knox, Ky., Apr. 1959.

2-169. Gogel, W. C., Mertens, H. W., Problems in Depth Perception: Perceived Size and Distance of Familiar Objects, FAA-AM-66-22, Federal Aviation Agency, Oklahoma City, Okla., 1966.

2-170. Gogel, W. C., The Size Cue to Visually Perceived Distance, FAA-AM-64-13, Federal Aviation Agency, Oklahoma City, Okla., 1964.

2-171. Gogel, W. C., Size Cues and the Adjacent Principle, FAA-CARI-63-28, Federal Aviation Agency, Oklahoma City, Okla., 1963.

2-172. Gogel, W. C., A Test of the Invariance of the Ratio of Perceived Size to Perceived Distance, Amer. J. Psychol., 76: 537-553, 1963.

2-173. Gogel, W. C., The Visual Perception of Size and Distance, FAA-CARI-62-15, Federal Aviation Agency, Oklahoma City, Okla., 1962.

2-174. Gogel, W. C., The Visual Perception of Spatial Extent, FAA-CARI- 63-20, Federal Aviation Agency, Oklahoma City, Okla., 1963.

2-175. Goldman, L., Dermatologic Manifestations of Laser Radiation, Fed. Proc., Suppl. 14: S92-S93, 1965.

2-176. Gordon, D. A., Rothstein, E. C., Ultra-violet Absorbers, Chemicals and Additives, in Modern Plastics Encyclopedia, for 1966, Vol. 43 1A, McGraw-Hill, N. Y., Sept. 1965, pp. 434-456.

2-177. Graham, C. H., (ed.), Vision and Visual Perception, John Wiley & Sons, Inc., N. Y., 1965.

2-178. Graham, C. H., Visual Perception, in Handbook of Experimental Psychology, Stevens, S. S., (ed.), John Wiley & Sons, N. Y., 1951, pp. 868-920.

2-179. Gregory, R. L., Distortion of Visual Space as Inappropriate Constancy Scaling, Nature, 199(4895): 678-680, 1963.

2-180. Gregory, R. L., Eye and Brain. The Psychology of Seeing, World University Library, McGraw-Hill, N. Y., 1966.

2-181. Gregory, R. L., Zangwill, O. L., The Origin of the Autokinetic Effect, Quart. J. Exp. Psychol., 15: 252-261, 1963.

2-182. Gregory, R. L., Visual Perception of Movement, AFOSR-66-1532, Air Force Office of Scientific Research, Washington, D. C., 1966. (AD-637510).

2-183. Grether, W. F., Visual Search in the Space Environment, in Visual Capabilities in the Space Environment, Baker, C. A., (ed.), Pergamon Press, N. Y., 1965, pp. 29-35.

2-184. Grissom, V. I., Pilot's Flight Report, in Results of the Second U. S. Manned Suborbital Space Flight, July 21, 1961, NASA, Manned Spacecraft Center, Washington, D. C., 1961, pp. 47-58.

2-185. Grumman Aircraft Engineering Corp., Man-System Locomotion and Display Criteria for Extra-Terrestrial Vehicles, NASA-CR-71757, 1965.

2-186. Guignard, J. C., Irving, A., Effects of Low Frequency Vibration on Man, Engineering, 190: 364-367, 1960.

2-187. Gulledge, I. S., Koomen, M. J., Packer, D. M., et al., Visual Thresholds for Detecting an Earth Satellite, Science, 127: 1242-1243, 1958.

2-188. Gunn, W. J., Loeb, M., Correlation of Performance in Detecting Visual and Auditory Signals, AMRL-713, Army Medical Research Lab., Fort Knox, Ky., Jan. 1967.

2-189. Guth, S. K., McNelis, J. F., A Discomfort Glare Evaluator, Illum. Engin., 54: 398-406, 1959

2-190. Guth, S. K., Eastman, A. A., Lighting for the Forgotten Man, Amer. J. Opt., 32: 413-421, 1955.

2-191. Guth, S. K., A Method for the Evaluation of Discomfort Glare, paper presented at National Technical Conference of the Illuminating Engineering Society, Dallas, Texas, Sept. 9-14, 1962. (Preprint No. 45).

2-192. Haig, C., The Course of Rod Dark Adaptation as Influenced by Intensity and Duration of Preadapting to Light, J. Gen. Physiol., 24: 735-751, 1941.

2-193. Haines, R. F., Changes in Size and Shape of a Highly Luminous Target, NASA, Ames Research Center, Moffett Field, Calif., 1966. (unpublished study).

2-194. Haines, R. F., The Effects of High Luminance Sources upon the Visibility of Point Sources, NASA-TM-X-56561, 1965.

2-195. Hall, M. V., Greenbaum, L. J., The Areas of Vision and Cockpit Visibility, Trans. Amer. Acad. Ophthal., 55: 74-88, Sept-Oct. 1950.

2-196. Ham, W. T., Jr., Wiesinger, H., Schmidt, F. H., et al., Flash Burns in the Rabbit Retina as a Means of Evaluating the Retinal Hazard from Nuclear Weapons, Amer. J. Ophth., 46: 700-723, 1958.

2-197. Ham, W. T., Jr., Williams, R. C., Mueller, H. A., et al., Ocular Effects of Laser Radiation, Part I, Acta Ophth., 43: 390-409, 1965.

2-198. Hamer, H. A., Mayo, A. P., Error Analysis of Several Methods of Determining Vehicle Position in Earth-Moon Space from Simultaneous Onboard Optical Measurements, NASA-TN-D-1805, June 1963.

2-199. Hanes, R. M., Williams, S. B., Visibility on Cathoderay Tubes: The Effects of Light Adaptation, J. Opt. Soc. Amer., 38: 363-377, 1948.

2-200. Hannah, M. E., Mayo, A. P., A Study of Factors Affecting the Accuracy of Position Fix for Lunar Trajectories, NASA-TN-D-2178, Jan. 1964.

2-201. Harcum, E. R., Rabe, A., Blackwell, H. R., Visual Recognition Along Various Meridians of the Visual Field, Project Michigan, Vision Res. Labs., Willow Run Labs., Univ. of Michigan, Ann Arbor, Mich. I. Preliminary Experiments, Rep. 2144-50-T, June 1957. II. Nine-Element Typewritten Targets, Rep. 2144-293-T, Dec. 1958. III. Patterns of Blackened Circles in an Eight-Circle Template, Rep. 2144-294-T, Nov. 1958. (AD-210340). IV. Linear Binary Patterns at Thirty-Six Orientations, Rep. 2144-296-T, Nov. 1958. (AD-208220). V. Binary Patterns Along 12 Meridians, Rep. 2144-302-T, Nov. 1958. (AD-206346). VI. 8-Element and 10-Element Binary Patterns, Rep. 2144-303-T, Nov. 1958. (AD-209357). VII. Effect of Target Length Measured in Angular Units, Rep. 2144-304-T, Nov. 1958. (AD-209358). VIII. Patterns of Solid Circles and Squares, Rep. 2144-306-T, Dec. 1958. (AD-210598). IX. Monocular and Binocular Recognition of Patterns of Squares and Circles, Rep. 2144-307-T, Nov. 1958. (AD-208332). X. Binary Patterns of the Letters "H" and "O", Rep. 2144-308-T, Nov. 1958. (AD-206295). XI. Identification of the Number of Blackened Circles, Rep. 2144-314-T, Dec. 1958. (AD-210599).

2-202. Harris, W., The Object Identification Test: A Stress-Sensitive Perceptual Test, Technical Report 209-1, Human Factors Research, Inc., Goleta, Calif., Feb. 1967.

2-203. Hartridge, H., The Chromatic Aberration of the Human Eye and Its Physiological Correction, Experientia, 6: 1-10, 1950.

2-204. Hartridge, H., The Visual Perception of Fine Detail, Phil. Trans., 232: 516, 1925.

2-205. Hatch, H. G., Jr., Rendezvous Docking Simulator, in A Compilation of Recent Research Related to the Apollo Mission, NASA-TM-X-890, 1963, pp. 187-192.

2-206. Hatch, H. G., Jr., Pennington, J. E., Cobb, J. B., Dynamic Simulation of Lunar Module Docking with Apollo Command Module in Lunar Orbit, NASA-TN-D-3972, 1967.

2-207. Hatch, H. G., Jr., Riley, D. R., Cobb, J. B., Simulating Gemini-Agena Docking, Astronaut. Aeron., 2: 74-81, 1964.

2-208. Hayes, J. R., Wolbarsht, M., A Thermal Theory of Laser Induced Retinal Damage, in Preprints of Scientific Program, 1967 Annual Scientific Meeting, Aerospace Medical Association, April 10-13, 1967, Washington, D. C., pp. 296-297.

2-209. Heap, E., Air to Ground Applications of Visual Detection Lobe Theory, RAE-TN-ARM-715, Royal Aircraft Establishment, Ministry of Aviation, London, Jan. 1962.

2-210. Hecht, S., Haig, C., Wald, G., The Dark Adaptation of Retinal Fields of Different Size and Location, J. Gen. Physiol., 19: 321-339, 1935.

2-211. Hecht, S., Shlaer, S., Verrijp, C. D., Intermittent Stimulation by Light, J. Gen. Physiol., 17: 237-282, Nov. 1933.

2-212. Hecht, S., Ross, S., Mueller, C. G., The Visibility of Lines and Squares at High Brightnesses, J. Opt. Soc. Amer., 37: 500-507, 1947.

2-213. Hecht, S., Williams, R. F., The Visibility of Monochromatic Radiation and the Absorption Spectrum of Visual Purple, J. Gen. Physiol., 5: 1-33, Sept. 1922.

2-214. Henschke, U., Schultze, R. Untersuchungen zum Problem der Ultraviolett-Dosimetrie. III. Über Pigmentierung durch langwelliges Ultraviolett, Strahlentherapie, 64: 14-42, 1939.

2-215. Henschke, U., Schultze, R., Untersuchungen zum Problem der Ultraviolett-Dosimetrie, IV. Wirkung der Sonnenstrahlung auf die Haut, Strahlentherapie, 64: 43-58, 1939.

2-216. Hill, J. H., Chisum, G. T., Effective Density of the Class 3 Visors, NADC-ML-L6501, Naval Air Development Center, Johnsville, Pa., May 1965.

2-217. Hill, N. E. G., The Recognition of Colored Light Signals which are Near the Limit of Visibility, Proc. Phys. Soc., (London), 59: 560-564, 1947.

2-218. Hoisman, A. J., Moots, A., The Use of a Visual Testing Apparatus for Space Application, Final Report, NASA-CR-73099, Apr. 1967.

2-219. Holladay, L. L., The Fundamentals of Glare and Visibility, J. Opt. Soc. Amer., 12(4): 271-319, Apr. 1926.

2-220. Hornick, R. J., Costin, R. W., Space Vehicle Vibration Effects on Human Occupants, paper presented at the Annual Meeting of the Aerospace Medical Association, April 9, 1962, Atlantic City, N. J.

2-221. Huston, T. O., Human Biological Interactions with Laser Light, NEL-1502, Naval Electronics Lab. Center, San Diego, Calif., Aug. 1967.

2-222. I. E. S., Lighting Handbook, Illuminating Engineering Society, N. Y., 3rd Edition, 1959.

2-223. Ireland, F. H., Effects of Surround Illumination on Visual Performance, An Annotated Bibliography, AMRL-TR-67-103, Aerospace Medical Research Labs., Wright-Patterson AFB, Ohio, 1967.

2-224. Ireland, F. H., Kinslow, W., Levin, E., et al., Experimental Study of the Effects of Surround Brightness and Size on Visual Performance, AMRL-TR-67-102, Aerospace Med. Res. Labs., Wright-Patterson AFB, Ohio, Sept. 1967.

2-225. Ivanoff, A., Chromatic Aberration of the Eye, Documenta Ophthalmologica, 3: 322-323, 1949.

2-226. Ivanoff, A., Les Aberrations de Chromatisme et de Sphericité de l'oeil, Rev. Opt., 26: 145-171, 1947.

2-227. Jaffe, L. D., Shoemaker, E. M., Dwornik, S. E., et al., Surveyor I Mission Report, Part II. Scientific Data and Results, JPL-TR-32-1023(Pt. 2), Jet Propulsion Laboratory, California Institute of Technology, Pasadena, Calif., 1966.

2-228. Jaquet, B. M., Riley, D. R., An Evaluation of Gemini Hand Controllers and Instruments for Docking, NASA-TM-X-1066, Mar. 1965.

2-229. Jaquet, B. M., Riley, D. R., Fixed-Base Gemini-Agena Docking Simulation, in A Compilation of Recent Research Related to the Apollo Mission, NASA-TM-X-890, 1963, Chapt. 9, pp. 67-78.

2-230. Jaquet, B. M., Simulator Studies of Space and Lunar Landing Techniques, in Lectures in Aerospace Medicine, School of Aerospace Med., Feb. 3-7, 1964, Brooks AFB, Texas, 1964, pp. 145-166.

2-231. Jayle, G. E., Ourgaud, A. G., Baisinger, L. F., et al., Night Vision, Charles C. Thomas, Springfield, Ill., 1959.

2-232. Jerison, J. H., Pickett, R. M., Stenson, H. H., The Elicited Observing Rate and Decision Processes in Vigilance, Human Factors, 7: 107-128, 1965.

2-233. Jerison, H. J., Pickett, R. M., Vigilance: A Review and Re-evaluation, in Visual Capabilities in the Space Environment, Baker, C. A., (ed.), Pergamon Press, N. Y., 1965, pp. 37-64.

2-234. Johansson, G., Ottander, C., Recovery Time after Glare. An Experimental Investigation of Glare After-Effect under Night Driving Conditions, Scand. J. Psychol., 5: 17-25, 1964.

2-235. Johnston, D. M., Search Performance as a Function of Peripheral Acuity, Human Factors, 7: 527-535, 1965.

2-236. Johnston, W. A., Howell, W. C., Influence of Prolonged Viewing of Large-Scale Displays on Extraction of Information, RADC-TR-67-411, Rome Air Development Center, Griffiss AFB, N. Y., Sept. 1967.

2-237. Jones, D. E., Comment on "Eye Protection Criteria for Laser Radiation", (Revised comment on UCRL-7811, pp. 14-19), in Hazards Control Quarterly Report No. 17, UCRL-12004, Lawrence Radiation Lab., Univ. of California, Livermore, Calif., 1964, pp. 37-38.

2-238. Jones, D. E., Montan, D. N., Eye Protection Criteria for Laser Radiation, in Hazards Control Quarterly Report No. 16, UCRL-7811, Lawrence Radiation Lab., Univ. of California, Livermore, Calif., 1964, pp. 14-19.

2-239. Jones, D. E., Sykos, M., The Laser Eye Protection Program at LRL, in Hazards Control Quarterly Report No. 18, UCRL-12167, Lawrence Radiation Lab., Univ. of California, Livermore, Calif., 1964, pp. 34-38.

2-240. Jones, M. R., Color Coding, Human Factors, 4: 355-365, 1962.

2-241. Jones, W. L., Allen, W. H., Parker, J. F., Advanced Vision Research for Extended Spaceflight, Aerospace Med., 38(5): 475-478, 1967.

2-242. Jones, W. L., Parker, J. F., Flash Blindness Protection, ACLANT Medical Officers Symposium on Biomedical Effects of Nuclear Weapons, National Naval Medical Center, Bethesda, Md., Oct. 29, 1963.

2-243. Kasten, F., Horizontal Visual Range in Polar Whiteout, USACRREL-SR-54, Army Cold Regions Research and Engineering Lab., Hanover, N. H., May 1962. (AD-653149).

2-244. Katzoff, S., The Electromagnetic-Radiation Environment of a Satellite. Part I. Range of Thermal to X-Radiation, NASA-TN-D-1360, Sept. 1962.

2-245. Kent, P. R., Vision Underwater, NMRL-498, Naval Submarine Medical Center, Submarine Base, Groton, Conn., July 1967.

2-246. Kinney, J. A. S., Cooper, J. C., Adaptation to a Homochromatic Visual World, NMRL-499, Naval Submarine Medical Center, Submarine Base, Groton, Conn., July 1967.

2-247. Kinney, J. A. S., Color Induction Using Asynchronous Flashes, NMRL-496, Naval Submarine Medical Center, Submarine Base, Groton, Conn., 1967. (Reprinted from Vision Res., 7: 299-318, 1967).

2-248. Kinney, J. A. S., Connors, M. M., Recovery of Foveal Acuity Following Exposure to Various Intensities and Durations of Light, NMRL-464, Naval Medical Research Lab., Groton, Conn., Dec. 1965. (Reprinted from Amer. J. Psychol., 78: 432-440, Sept. 1965)

2-249. Kinney, M., Occupational Laser Hazards - A Survey of the Literature, Rep. T5-1245/3111, Autonetics, Div. of North American Aviation, Inc., Downey, Calif., 1965. (AD-617913).

2-250. Koller, L. R., Ultraviolet Radiation, John Wiley & Sons, N. Y., 2nd Ed., 1965.

2-251. Koomen, M., Tousey, R., Scolnik, R., Spherical Aberration of the Eye, J. Opt. Soc. Amer., 39: 370-376, 1949.

2-252. Koopman, B. O., Search and Screening, OEG Rep. 56, Operations Evaluation Group, Office of the Chief of Naval Operations, Navy Department, Washington, D. C., 1946.

2-253. Kopal, Z., The Moon Our Nearest Celestial Neighbor, Academic Press, N. Y., 1960.

2-254. Kosenkov, M. M., Kuz'minov, A. P., Some Results and Problems of Observation under Spaceflight Conditions, FTD-TT-65-1/1, Foreign Technology Division, Wright-Patterson AFB, Ohio, Jan. 10, 1965. (Source: III International Symposium on Bioastronautics at San Antonio, Texas, Nov. 16-18, 1964, pp. 3-7).

2-255. Lamar, E. S., Operational Background and Physical Considerations Relative to Visual Search Problems, in Visual Search Techniques, Proceedings of a Symposium, Apr. 7-8, 1959, Washington, D. C., Morris, A., Horne, E. P., (eds.), NAS-NRC-712, 1960, pp. 1-9.

2-256. Lamar, E. S., Hecht, S., Shlaer, S., et al., Size, Shape, and Contrast in Detection of Targets by Daylight Vision, I. Data and Analytical Description, J. Opt. Soc. Amer., 37: 531-545, 1947.

2-257. Landis, D., Slivka, R. M., Jones, J. M., et al., Evaluation of Large Scale Visual Displays, RADC-TR-67-57, Rome Air Development Center, Griffiss AFB, N. Y., 1967. (AD-651372).

2-258. Landis, D., Slivka, R. M., Jones, J. M., et al., Experiments in Display Evaluation, Technical Rep. 1-194, The Franklin Institute Research Labs., Philadelphia, Pa., July 1967.

2-259. Lash, J. D., Prideaux, G. F., Visibility of Signal Lights, Illum. Engin., 38: 481-492, 1943.

2-260. LeGrand, Y., Light, Color and Vision, John Wiley & Sons, N. Y., 1957, p. 104.

2-261. Lewis, M. F., Mertens, H. W., Reaction Time as a Function of Flash Luminance and Duration, FAA-AM-67-24, Federal Aviation Administration, Office of Aviation Medicine, Oklahoma City, Okla., Nov. 1967.

2-262. Lichtenstein, J. H., Suit, W. T., An Experimental Investigation of Two Visual Methods of Altitude Determination, NASA-TM-X-1392, May 1967.

2-263. Lina, L. J., Assadourian, A., Investigation of the Visual Boundary for Immediate Perception of Vertical Rate of Descent, NASA-TN-D-1591, 1963.

2-264. Lineberry, E. C., Jr., Brissenden, R. F., Kurbjun, M. C., Analytical and Preliminary Simulation of a Pilot's Ability to Control the Terminal Phase of a Rendezvous with Simple Optical Devices and a Timer, NASA-TN-D-965, Oct. 1961.

2-265. Ling-Temco-Vought, Inc., NASA Lunar Module Visual Simulation Study, Vol. I - Lunar Mission Descent, Ascent, and Rendezvous, LTV-00.884 (Vol. I), 1966. Vol. II - Lunar Module Rendezvous in Earth Orbit, LTV-00.884(Vol. 2), 1967.

2-266. Lippert, S., Lee, D. M., Dynamic Vision: The Legibility of Moderately Spaced Alphanumeric Symbols, Human Factors, 7: 555-560, 1965.

2-267. Litwin, M. S., Glew, D. H., The Biological Effects of Laser Radiation, JAMA, 187, 842-847, 1964.

2-268. Litwin, M. S., Earl, K. M., (eds.), Proceedings of the First Annual Conference on Biologic Effects of Laser Radiation, Armed Forces Institute of Pathology, Washington, D. C., 30 April-1 May 1964, Fed. Proc., 24: 1, Part 3, Suppl. No. 14, pp. S1-S177, Jan-Feb. 1965.

2-269. Long, E. R., Jr., Pennington, J. E., Deal, P. L., Remote Pilot-Controlled Docking with Television, NASA-TN-D-3044, Oct. 1965.

2-270. Luce, T. S., Vigilance as a Function of Stimulus Variety and Response Complexity, Human Factors, 6: 101-110, 1964.

2-271. Luckiesh, M., Brightness Engineering, Illum. Engin., 39: 75-92, 1944.

2-272. Luckiesh, M., Guth, S. K., Brightness in Visual Field at Borderline between Comfort and Discomfort, Illum. Engin., 44: 650-670, 1949.

2-273. Luckiesh, M., Moss, F. K., The New Science of Seeing, in Interpreting the Science of Seeing into Lighting Practice, Vol. 1, General Electric Co., Cleveland, Ohio, 1927-1932.

2-274. Ludvigh, E., Miller, J. W., Study of Visual Acuity during the Ocular Pursuit of Moving Test Objects, J. Opt. Soc. Amer., 48(11): 799-802, Nov. 1958.

2-275. Luria, S. M., Color-Name as a Function of Stimulus Intensity and Duration, NMRL-494, U. S. Naval Submarine Medical Center, Submarine Base, Groton, Conn., 1967.

2-276. Luria, S. M., Effects of Continuously and Discontinuously Moving Stimuli on the Luminance Threshold of a Stationary Stimulus, NMRL-454, Naval Submarine Medical Center, Submarine Base, Groton, Conn., 1965.

2-277. Luria, S. M., Kinney, J. A. S., The Interruption of Dark Adaptation, NMRL-347, Naval Medical Research Lab., Submarine Base, Groton, Conn., Feb. 1961.

2-278. Lythgoe, R. J., The Measurement of Visual Acuity, Rep. No. 173, Medical Research Council, London, England, 1932.

2-279. McCartney, A. J., A Consideration of the Biological Effects of Laser, AMRL-654, Army Medical Research Laboratory, Fort Knox, Ky., 1966. (Also in: Mil. Med., 130: 1069-1077, Nov. 1965).

2-280. McCormick, E. J., Human Factors Engineering, McGraw-Hill, N. Y., 1957.

2-281. McFarland, R. A., Human Factors in Air Transportation: Occupational Health and Safety, McGraw-Hill, N. Y., 1953.

2-282. Mackworth, N. H., Researches on the Measurement of Human Performance, Medical Research Council Special Report Series 268, H. M. Stationery Office, London, England, 1950. Reprinted in Selected Papers on Human Factors in the Design and Use of Control Systems, Sinaiko, H. W., (ed.), Dover, N. Y., 1961, pp. 174-331.

2-283. McLean, M. V., Brightness Contrast, Color Contrast and Legibility, Human Factors, 7: 521-526, 1965.

2-284. McPhail, C. D., Apollo External Visual Simulation Display Systems, AIAA-67-253, paper presented at AIAA Flight Test Simulation and Support Conference, Cocoa Beach, Fla., Feb. 6-8, 1967.

2-285. Mandelbaum, J., Rowland, L. S., Central and Paracentral Visual Acuity at Different Levels of Illumination, Project No. 220, Rep. No. 1, Air Force School of Aviation Medicine, Randolph Field, Texas, 1944.

2-286. Marriott, F. H. C., Visual Search by Night, APRC-66/NC3, Army Personnel Res. Comm. Medical Research Council, London, Sept. 1966. (AD-809474).

2-287. Martin, D. J., The Visibility of an Object in a Space Environment NASA-L-1872, presented at the 30th Annual Meeting, Institute of the Aeronautical Sciences, N. Y., Jan. 21-24, 1962.

2-288. Mayo, A. P., Jones, R. L., Adams, W. M., Accuracy of Navigation in Various Regions of Earth-Moon Space with Various Combinations of Onboard Optical Measurements, NASA-TN-D-2448, Sept. 1964.

2-289. Mayo, A. P., Hamer, H. A., Hannah, M. E., Equations for Determining Vehicle Position in Earth-Moon Space from Simultaneous Onboard Optical Measurements, NASA-TN-D-1604, Feb. 1963.

2-290. Melton, C. E., Higgins, E. A., Saldivar, J. T., et al., Exposure of Men to Intermittent Photic Stimulation under Simulated IFR Conditions, FAA-AM-66-39, Federal Aviation Agency, Oklahoma City, Okla., 1966.

2-291. Mercier, A., Whiteside, T. C. D., The Effect of Red Versus White Instrument Lighting on the Dark Adaptation Index, FPRC-1255, Flying Personnel Research Comm., Ministry of Defense, London, May 1966.

2-292. Metcalf, R. D., Horn, R. E., Visual Recovery Times from High Intensity Flashes of Light, WADC-TR-58-232, Wright Air Dev. Center, Wright-Patterson AFB, Ohio, 1958.

2-293. Middleton, W. E. K., Vision Through the Atmosphere, Univ. of Toronto Press, Toronto, 1958.

2-294. Miller, G. K., Jr., Fixed-Base Visual-Simulation Study of Manually Controlled Translation and Hover Maneuvers Over the Lunar Surface, NASA-TN-D-3653, Oct. 1966.

2-295. Miller, G. K., Jr., Sparrow, G. W., Visual Simulation of Lunar Orbit Establishment Using a Simplified Guidance Technique, NASA-TN-D-3524, 1966.

2-296. Miller, J. W., Study of Visual Acuity during the Ocular Pursuit of Moving Test Objects, II. Effects of Direction of Movement, Relative Movement, and Illumination, J. Opt. Soc. Amer., 48(11): 803-808, Nov. 1958.

2-297. Miller, N. D., Visual Recovery, SAM-TR-65-12, School of Aerospace Medicine, Brooks AFB, Texas, 1965.

2-298. Miller, N. D., Visual Recovery from High Intensity Flashes II, Final Rep., Contract AF41(609)-2426, Ohio State Univ., Columbus, Ohio, 1966. (AD-642731).

2-299. Montague, W. E., Webber, C. E., Adams, J. A., The Effects of Signal and Response Complexity on Eighteen Hours of Visual Monitoring, Human Factors, 7: 163-172, 1965.

2-300. Moon, P., Proposed Standard Solar-Radiation Curves for Engineering Use, J. Franklin Inst., 230: 583-618, 1941.

2-301. Moon, P., Scientific Basis of Illuminating Engineering, Dover Publications, Inc., N. Y., 1936. (Paperback Edition).

2-302. Moon, P., Spencer, D. E., Visual Data Applied to Lighting Design, J. Opt. Soc. Amer., 34: 605-617, Oct. 1944.

2-303. Moran, J. A., Tiller, P. R., Investigation of Aerospace Vehicle Crew Station Criteria, AFFDL-TDR-64-86, Flight Dynamics Lab., Wright-Patterson AFB, Ohio, July 1964.

2-304. Morgan, C. T., Cook, J. S., III., Chapanis, A., et al., Human Engineering Guiue to Equipment Design, McGraw-Hill, N. Y., 1963.

2-305. Morris, A., Horne, E. P., (eds.), Visual Search Techniques, Proceedings of Symposium sponsored by the Armed Forces NRC Committee on Vision, NAS-NRC Publ. 712, National Academy of Sciences - National Res. Council, Washington, D. C., 1960.

2-306. Mote, F. A., Riopelle, A. J., The Effect of Varying the Intensity and the Duration of Pre-exposure upon Subsequent Dark Adaptation in the Human Eye, J. Comp. Physiol. Psychol., 46: 49-55, 1953.

2-307. Muller, A. F., Wilson, P. W., Jr., Eye Effects Mathematical Models, Project Task No. 630103, School of Aerospace Medicine, Brooks AFB, Texas, June 1967. (AD-653984).

2-308. Muller, A. F., Wilson, P. W., Jr., Research Toward the Development of Eye Effects Safe Separation Charts, Final Rep., Contract AF41(609)-2437, Technology, Inc., San Antonio, Texas, July 1966. (AD-641191).

2-309. Munsell, A. H., Munsell Book of Color, Munsell Color Book Co., Inc., Baltimore, 1942.

2-310. Munsell, A. H., Munsell Book of Color. Defining, Explaining and Illustrating the Fundamental Characteristics of Color; A Revision and Extension of the Atlas of the Munsell Color System, Munsell Color Book Co., Baltimore, Md., 1929.

2-311. Murrell, K. F. H., Laurie, W. D., McCarthy, C., The Relationship between Dial Size, Reading Distance and Reading Accuracy, Ergonomics, 1: 182-190, 1958.

2-312. Nachmias, J., Brightness and Visual Acuity with Intermittent Illumination, J. Opt. Soc. Amer., 48(10): 726-730, 1958.

2-313. Narva, M. A., Muckler, F. A., Visual Surveillance and Reconnaissance from Space Vehicles, in Visual Capabilities in the Space Environment, Baker, C. A., (ed.), Pergamon Press, N. Y., 1965, pp. 121-141.

2-314. National Aeronautics and Space Administration, Manned Spacecraft Center, Houston, Texas, Gemini Midprogram Conference Including Experiment Results, NASA-SP-121, 1966.

2-315. National Aeronautics and Space Administration, Lasers and Masers, A Continuing Bibliography with Indexes, NASA-SP-7009 (01), July 1966.

2-316. National Aeronautics and Space Administration, Natural Environment and Physical Standards for the Apollo Program, NASA-M-DE-8020-008B, Office of Manned Spaceflight, Washington, D. C., Apr. 1965.

2-317. National Aeronautics and Space Administration, Results of the First United States Manned Orbital Space Flight, Manned Spacecraft Center, Houston, Texas, Feb. 20, 1962.

2-318. National Aeronautics and Space Administration, Surveyor I, A Preliminary Report, NASA-SP-126, June 1966.

2-319. Ney, E. P., Huch, W. F., Optical Environment in Gemini Space Flights, Science, 153: 297-299, 1966.

2-320. Norris, R. E., Gouyd, C. A., The Effect of Simulated TOW Launch Transients on Operator Tracking, HAC-TM-HM-88, Hughes Aircraft Co., Culver City, Calif., 1964.

2-321. Norris, R. E., Gouyd, C. A., HLMR Acquisition and Tracking Field Trials, Phase II, Sight Evaluation, HAC-IDC-2732-50/92, Hughes Aircraft Co., Culver City, Calif., 1964.

2-322. Nutting, P. G., Effects of Brightness and Contrast in Vision, Trans. Illum. Engin. Soc., 11: 939-946, 1916.

2-323. Nutting, P. G., Report of Standards of Committee on Visual Sensitometry, J. Opt. Soc. Amer., 4: 55-79, 1920.

2-324. O'Brien, P. F., Numerical Analysis for Lighting Design, Illum. Engin., 60: 169-178, Apr. 1965.

2-325. Ogle, K. N., On the Resolving Power of the Human Eye, J. Opt. Soc. Amer., 41: 517-520, 1951.

2-326. Olenski, Z., Goodden, N. W., Clearness of View from Day-Fighter Aircraft, (Part of "Ability to See"), RAE-Aero-1862, Royal Aircraft Establishment, Farnborough, England, Oct. 1943. (AD-115868).

2-327. Optical Society of America, Committee on Colorimetry, The Science of Color, Thomas Y. Crowell Co., N. Y., 1953.

2-328. Orlova, N. S., Selected Articles on Light Scattering and Photometric Relief of the Lunar Surface, NASA-TT-F-75, Sept. 1962. (Translation of article in Astronomicheskiy Zhurnal, Akademii Nauk SSSR, 33(1): 93-100, 1956).

2-329. Otero, J. M., Plaza, L., Salavarri, F., Absolute Threshold and Night Myopia, J. Opt. Soc. Amer., 39: 167, 1949.

2-330. Otero, J. M., Influence of the State of Accomodation on the Visual Performance of the Human Eye, J. Opt. Soc. Amer., 41: 942-948, 1951.

2-331. Otis, L. S., The Effects of Drugs on Vision, in Recent Developments in Vision Research, Whitcomb, M. A., (ed.), NAS-NRC 1272, National Academy of Sciences - National Res. Council, Washington, D. C., 1966, pp. 216-222.

2-332. Parker, J. F., Target Visibility as a Function of Light Transmission Through Fixed Filter Visors, Rep. 64-2, Bio-Technology, Inc., Arlington, Va., 1964.

2-333. Partington, M. W., The Vascular Response of the Skin to Ultraviolet Light, Clin. Sci., 13: 425-439, 1954.

2-334. Pennington, J. E., Effects of Display Noise on Pilot Control of the Terminal Phase of Space Rendezvous, NASA-TN-D-1619, 1963.

2-335. Pennington, J. E., Some Aspects of Man's Visual Capabilities in Space, in A Compilation of Recent Research Related to the Apollo Mission, NASA-TM-X-890, 1963, pp. 59-65.

2-336. Pennington, J. E., Brissenden, R. F., Visual Capability of Pilots as Applied to Rendezvous Operations, IAS-Paper 63-15, presented at the IAS 31st Annual Meeting, N. Y., Jan. 21-23, 1963.

2-337. Pennington, J. E., Hatch, H. G., Jr., Long, E. R., et al., Visual Aspects of a Full-Size Pilot-Controlled Simulation of the Gemini-Agena Docking, NASA-TN-D-2632, 1965.

2-338. Pepler, R. D., Wohl, J. G., Display Requirements for Prelaunch Checkout of Advanced Space Vehicles, RAND-RM-4200-NASA, RAND Corp., Santa Monica, Calif., May 1964.

2-339. Peskin, J. C., Bjornstad, J., The Effect of Different Wavelengths of Light on Visual Sensitivity, AML-MR-694-93A, Air Materiel Command, Wright-Patterson AFB, Ohio, 1948.

2-340. Peters, G. A., Adams, B. B., These Three Criteria for Readable Panel Markings, Product Engineering, 30(21): 55-57, 1959.

2-341. Petertyl, S. V., Fuller, P. R., Wysocki, C. A., et al., Development of High Contrast Electroluminescent Displays, AFFDL-TR-66-183, Flight Dynamics Lab., Wright-Patterson AFB, Ohio, Mar. 1967.

2-342. Pitha, C. A., Laser Damage: A Selected Literature Survey, AFCRL-67-137, Air Force Cambridge Research Labs., L. G. Hanscom Field, Bedford, Mass., 1967.

2-343. Pomerantzeff, O., Enhancement of Night Vision by Correction of Optical Aberrations of the Eye, Rep. 1, Retina Foundation, Department of Retina Research, Boston, Mass., under contract DADA-17-67-C-0029, Army Medical Research and Development Command, Washington, D. C., Apr. 1967. (AD-815995).

2-344. Popov, V., Boyko, N., Vision in Space Travel, RSIC-698, Redstone Scientific Information Center, Redstone Arsenal, Ala., Aug. 1967. (Translation of Aviatsiya i Kosmonautika, No. 3: 73-76, 1967).

2-345. Potts, A. M., Ocular Pharmacodynamics, in Recent Developments in Vision Research, Whitcomb, M. A., (ed.), NAS-NRC, Publ. 1272, 1966, pp. 192-193.

2-346. Putnam, R. C., Faucett, R. E., The Threshold of Discomfort Glare at Low Adaptation Levels, Illum. Engin., 46: 505-510, Oct. 1951.

2-347. Richards, W., Luria, S. M., Color Mixture Functions at Low Luminance Levels, NMRL-439, Naval Submarine Medical Center, Submarine Base, Groton, Conn., 1964. (Reprinted from: Vision Res., 4: 281-313, 1964).

2-348. Riley, D. R., Jaquet, B. M., Pennington, J. E., et al., Comparison of Results of Two Simulations Employing Full-Size Visual Cues for Pilot-Controlled Gemini-Agena Docking, NASA-TN-D-3687, 1966.

2-349. Riley, D. R., Jaquet, B. M., Cobb, J. B., Effect of Target Angular Oscillations on Pilot-Controlled Gemini-Agena Docking, NASA-TN-D-3403, 1966.

2-350. Riley, D. R., Jaquet, B. M., Bardusch, R. E., et al, A Study of Gemini-Agena Docking Using a Fixed-Base Simulator Employing a Closed-Circuit Television System, NASA-TN-D-3112, 1965.

2-351. Ritter, O. L., Strughold, H., Seeing Planets from Space, Astronautics and Aerospace Engineering, 1(6): 82-87, July 1963.

2-352. Roach, F. E., The Light of the Night Sky: Astronomical Interplanetary and Geophysical, Space Science Reviews, 3(4): 512-540, 1964.

2-353. Roberts, L., The Action of a Hypersonic Jet on a Dust Layer, IAS-63-50, Inst. Aerospace Science, Annual Meeting, 31st, N. Y., Jan. 21-23, 1963.

2-354. Robinson, N., (ed.), Solar Radiation, Elsevier Publishing Co., Amsterdam, 1966.

2-355. Rocco, R. M., Research and Development of Helmet Face-pieces for Space Protective Assemblies, AMRL-TR-66-193, Aerospace Medical Res. Labs., Wright-Patterson AFB, Ohio, 1967.

2-356. Ronchi, L., Freedman, S. J., Comparative Study of Acquisition Times for Various Visual Functions, Serie II, No. 1103, Pubblicazioni Dell' Istituto Nazionale di Ottica, Arcetri-Firenze, 1965. (Reprinted from: Atti Fond. G. Ronchi, 20(1): 88-101, Jan-Feb. 1965).

2-357. Ronchi, L., Tittarelli, R., Detection of Circular Light Signals in Relation to Shape and Color Identification, Preliminary Report, SAM-TR-66-14, School of Aerospace Med., Brooks AFB, Texas, 1966.

2-358. Ronchi, L., Sulli, R., Low Luminance Background: A Handicap for Signal Perception, Atti. Fond. G. Ronchi, 21(6): 729-737, Nov-Dec. 1966.

2-359. Ronchi, L., On the Factors Influencing the Judgment of Brightness, Serie II, No. 1076, Pubblicazioni Dell' Istituto Nazionale di Ottica, Arcetri-Firenze, 1964. (Reprinted from: Atti. Fond. G. Ronchi, 19(4): 408-412, Jul-Aug. 1964).

2-360. Ronchi, L., Fujiwara, S., Tittarelli, R., Response to Low-Frequency Intermittent Stimulation and Visual Noise, Serie II, N. 1077, Pubblicazioni Dell' Istituto Nazionale di Ottica, Arcetri-Firenze, 1964. (Reprinted from: Atti. Fond. G. Ronchi, 19(4): 413-427, Jul-Aug. 1964).

2-361. Ronchi, L., Fujiwara, S., A Statistical Treatment of Irregularities of Scotopic Sensitivity, Serie II, No. 1070, Pubblicazioni Dell' Istituto Nazionale di Ottica, Arcetri-Firenze, 1964. (Reprinted from: Atti Fond. G. Ronchi, 19(3): 305-314, May-June 1964)

2-362. Ronchi, L., Bittini, M., Adachi, I., Subjective Sharpness of a Contour as a Function of Luminance and Contrast, Optik, 20: 132-140, 1963.

2-363. Rose, H. W., Nomograph of Equivalent Values of Commonly Used Units of Luminance, Table 2.2, in Vision in Military Aviation, Chapter 2. The Nature and Measurement of Light, Wulfeck, J. W., Weisz, A., Raben, M. W., et al, (eds.), WADC-TR-58-399, Nov. 1958, p. 16.

2-364. Roth, E. M., Bioenergetic Considerations in the Design of Space Suits for Lunar Exploration, NASA-SP-84, 1966.

2-365. Roth, E. M., Space-Cabin Atmospheres, Part II - Fire and Blast Hazards, NASA-SP-48, 1964.

2-366. Ruch, T. C., Fulton, J. F., (eds.), Medical Physiology and Biophysics, W. B. Saunders Co., Philadelphia, Pa., 1960.

2-367. Runyan, T. L., Dick, J. M., Illumination for Extravehicular Tasks, DAC-P-3876, Douglas Aircraft Co., Inc., Santa Monica, Calif., Mar. 1966.

2-368. Rushton, W. A. H., Cohen, R. D., Visual Purple Level and the Course of Dark Adaptation, Nature (London), 173: 301-302, 1954.

2-369. Russell, J. L., The Temporary Blinding Effect of Flashes of Light, Report No. E and I-1085, Royal Aircraft Establishment, South Farnborough, Hants, England, 1937.

2-370. Ryken, J. M., Emerson, J. E., Onega, G. T., et al., Study of Requirements for the Simulation of Rendezvous and Docking of Space Vehicles, AMRL-TDR-63-100, Aerospace Medical Res. Labs., Wright-Patterson AFB, Ohio, 1963.

2-383. Shepard, A. B., Pilot's Flight Report Including Inflight Films, in Proceedings of a Conference on Results of the First U. S. Manned Suborbital Space Flight, NASA, Manned Spacecraft Center, Houston, Texas, 1961, pp. 69-75.

2-384. Shlaer, S., Smith, E. L., Chase, A. M., Visual Acuity and Illumination in Different Spectral Regions, J. Gen. Physiol., 25: 553-569, Mar. 1942.

2-385. Siegel, A. I., Fischl, M. A., Dimensions of Visual Information Displays, Applied Psychological Services, Wayne, Pa., under Contract N00014-66-C0183, Office of Naval Research, Sept. 1967.

2-386. Simon, C. W., Craig, D. W., Effects of Magnification and Observation Time on Target Identification in Simulated Orbital Reconnaissance, Human Factors, 7: 569-583, 1965.

2-387. Simon, C. W., Rapid Acquisition of Radar Targets from Moving and Static Displays, Human Factors, 7: 185-205, 1965.

2-388. Sloan, L. L., Rate of Dark Adaptation and Regional Threshold Gradient of the Dark-Adapted Eye: Physiologic and Clinical Studies, Amer. J. Ophthal., 30: 705-720, 1947.

2-389. Smith, H. A., Goddard, C., Effects of Cockpit Lighting Color on Dark Adaptation, AFFDL-TR-67-56, Flight Dynamics Lab., Wright-Patterson AFB, Ohio, May 1967.

2-390. Smith, W. J., Gulick, W. L., Dynamic Contour Perception, J. Exp. Psychol., 53: 145-151, 1957.

2-391. Smith, W. M., Gulick, W. L., A Statistical Theory of Dynamic Contour Perception, Psychol. Rev., 69: 91-108, 1962.

2-392. Smith, W. M., Gulick, W. L., Visual Contours and Movement Perception, Science, 124: 316-317, 1956.

2-393. Snyder, E. F., Development of a Lunar Photometric Function from Experimental Data, Chrysler Corporation, in Proceedings of the Interdisciplinary Symposium on Apollo Application Programs (12-13 Jan. 1966), Society of Engineering Science, Huntsville, Ala., NASA-TM-X-53558, George C. Marshall Space Flight Center, Huntsville, Ala., Dec. 1966, pp. 61-116.

2-394. Spector, W. S., (ed.), Handbook of Biological Data, WADC-TR-56-273, Wright Air Dev. Center, Wright-Patterson AFB, Ohio, Oct. 1956. (AD-110501).

2-371. Schmidt, I., Satellite-to-Satellite Visibility, in Lectures in Aerospace Medicine, School of Aerospace Med., Brooks AFB, Texas, Feb. 3-7, 1964, pp. 100-118.

2-372. Schmidt, I., Space of Potential Visibility of Artificial Satellites for the Unaided Eye, in Proceedings of the International Astronautical Congress, 8th, Barcelona, 1958, p. 373.

2-373. Schober, H., Wittmann, K., Untersuchungen über die Sehschärfe bei verschiedenfarbigen Licht. Das Licht, Z. praktische Leucht-u. Beleuchtungs-Aufgaben, 8: 199-201, 1938.

2-374. Scott, T. H., Literature Review of the Intellectual Effects of Perceptual Isolation, Rep. HR-66, Dept. of National Defence, Defence Research Board, Canada, 1957.

2-375. Sears, F. W., Principles of Physics, in Optics, Vol. III, Sears, F. W., (ed.), Addison-Wesley Press, Cambridge, Mass., 1946, pp. 1-323.

2-376. Seminara, J. L., Kincaid, W. K., Jr., Control Task Performance in the Lunar Visual Environment, LMSC-685055, Biotechnology Organization, Lockheed Missiles & Space Co., Sunnyvale, Calif., Feb. 1968.

2-377. Senders, J. W., Elkind, J. I., Grignetti, M. C., et al., An Investigation of the Visual Sampling Behaviour of Human Observers, NASA-CR-434, 1966.

2-378. Severin, S. L., Recovery of Visual Discrimination After High Intensity Flashes of Light, SAM-62-16, School of Aerospace Med., Brooks AFB, Texas, Dec. 1961.

2-379. Severin, S. L., Newton, N. L., Culver, J. F., A Study of Photostress and Flash Blindness, SAM-TDR-62-144, School of Aerospace Med., Brooks AFB, Texas, 1962.

2-380. Seyb, E. K., Sighting Range at Night and Twilight Brightness, SHAPE-TM-151, SHAPE Technical Centre, The Hague, (Netherlands), Mar. 1967. (AD-811315).

2-381. Shea, R. A., Summers, L. G., Visual Detection of Point Source Targets, NASA-CR-563, 1966.

2-382. Shearer, J. E., Downey, P., Design Study for Cabin Lighting of Orbital Flight Vehicle, WADD-TR-60-122, Wright Air Development Division, Wright-Patterson AFB, Ohio, 1960.

2-395. Stair, R., Spectral-Transmissive Properties and Use of Eye-Protective Glasses, NBS-Circular-471, National Bureau of Standards, Washington, D. C., Oct. 8, 1948. (Also includes the Supplementary Notes on the Spectral Transmittance of Glasses for Driving at Night, (this accompanies NBS Circ-471), Nov. 10, 1955).

2-396. Steedman, W. C., Baker, C. A., Target Size and Visual Recognition, Human Factors, 2: 120-127, 1960.

2-397. Stiles, W. S., Crawford, B. H., The Luminous Efficiency of Rays Entering the Eye Pupil at Different Points, Proc. Roy. Soc. (London), 112B: 428-450, Mar. 1933.

2-398. Straub, W. H., Protection of the Human Eye from Laser Radiation, HDL-TR-1133, Harry Diamond Labs., Washington, D. C., July 1963.

2-399. Strughold, H., The Human Time Factor in Flight, II. Chains of Latencies in Vision, J. Aviat. Med., 22: 100-108, 1951.

2-400. Suchman, E. A., Weld, H. P., The Effect of Light Flashes during the Course of Dark Adaptation, Amer. J. Psychol., 51: 717-722, 1938.

2-401. Summers, L. G., Shea, R. A., Ziedman, K., Unaided Visual Detection of Target Satellites, J. Spacecraft, 3: 76-79, 1966.

2-402. Sytinskaya, N. N., Summary Catalog of the Absolute Values of the Visual Reflecting Power at Full Moon of 104 Lunar Objects, STL-TR-61-5110-24, Space Tech. Lab., Los Angeles, Calif., 1961.

2-403. Tanner, W. P., Jr., Swets, J. A., A Decision-Making Theory of Visual Detection, Psychol. Rev., 61: 401-409, 1954.

2-404. Taylor, J. B., Silverman, S. M., Some Aspects of Night Visibility Useful for Air Force Operations, AFCRL-66-862, Air Force Cambridge Research Labs., L. G. Hanscom Field, Bedford, Mass., 1966.

2-405. Taylor, J. G., The Behavioural Basis of Perceived Size and Distance, Canad. J. Psychol., 19: 1-14, Mar. 1965.

2-406. Taylor, J. H., Scripps Institution of Oceanography, Visibility Lab., Univ. of California, La Jolla, Calif., personal communication, 1968.

2-407. Taylor, J. H., Contrast Thresholds as a Function of Retinal Position and Target Size for the Light-Adapted Eye, SIO-Ref-61-10, Scripps Institution of Oceanography, Univ. of California, La Jolla, Calif., Mar. 1961.

2-408. Taylor, J. H., Practice Effects in a Simple Visual Detection Task, Nature, 201: 691-692, 1964.

2-409. Taylor, J. H., Survey of Research Relating to Man's Visual Capabilities in Space Flight, Final Report, under Contract NOBS-86012, Scripps Institution of Oceanography, Univ. of California, La Jolla, Calif., June 1964. (AD-606802).

2-410. Taylor, J. H., Visual Performance on the Moon, Scripps Institution of Oceanography, Univ. of California, San Diego, Calif., paper presented at the XVIIth Congress of the International Astronautical Federation, Madrid, Spain, Oct. 1966.

2-411. Thomson, M. L., Relative Efficiency of Pigment and Horny Layer in Protecting the Skin of Europeans and Africans against Solar Ultraviolet Radiation, J. Physiol., 127: 236-246, 1955.

2-412. Tinker, M. A., Lighting and Color, in Human Factors in Undersea Warfare, National Academy of Sciences - National Res. Council, Committee on Undersea Warefare, Washington, D. C., 1949, pp. 357-374.

2-413. Tousey, R., Report on Effect of CRT Screens on Night Vision, U. S. Naval Res. Lab., Washington, D. C.

2-414. Trumbull, R., Some Potential of Research on Drugs and Vision, in Recent Developments in Vision Research, Whitcomb, M. A., (ed.), NAS-NRC-1272, National Academy of Sciences - National Res. Council, Washington, D. C., 1966, pp. 223-225.

2-415. Tschermak-Seysenegg, A. von, Introduction to Physiological Optics, Charles C. Thomas, Springfield, Ill., 1952, p. 19.

2-416. Tufts Inst. for Appl. Exp. Psychol., Handbook of Human Engineering Data for Design Engineers, Tech. Rep. No. SDC-199-1-1, Tufts Univ., Medford, Mass., Revised 1951.

2-417. Uhlaner, J. E., Zeidner, J., The Army Night Seeing Tester, Development and Use, HFRB-TRR-1120, Human Factors Research Branch, TAG Research and Development Command, U. S. Army, May 1961. (AD-258349).

2-418. Ulett, G. A., Flicker Sickness, Arch. Ophthal., 50: 685-687, 1953.

2-419. Urmer, A. H., Jones, E. R., The Visual Subsystem Concept and Spacecraft Illumination, in Visual Capabilities in the Space Environment, Baker, C. W., (ed.), Pergamon Press, N. Y., 1965, pp. 101-109.

2-420. Vallerie, L. L., Peripheral Vision Displays, NASA-CR-808, 1967.

2-421. Valsi, E., Bartley, S. H., Bourassa, C., Further Manipulation of Brightness Enhancement, J. Psychol., 48: 47-55, 1959.

2-422. Vanderplas, J. M., Visual Capabilities of Performing Rendezvous in Space, in Visual Capabilities in the Space Environment, Baker, C. A., (ed.), Pergamon Press, N. Y., 1965, pp. 149-154.

2-423. Van Dyke, J. W., Performance/Design and Product Configuration Requirements, Extravehicular Mobility Unit for Apollo Block II Missions, CSD-A-096, NASA, Manned Spacecraft Center, Crew Systems Division, Houston, Texas, Jan. 1966.

2-424. Van Liere, E. J., Hypoxia, University of Chicago Press, Chicago, 1963.

2-425. Vassiliadis, A., Peppers, N. A., Peabody, R. R., et al., Investigations of Laser Damage to Ocular Tissues, AFAL-TR-67-170, Air Force Avionics Lab., Wright-Patterson AFB, Ohio, Mar. 1967.

2-426. Verhoeff, F. H., Bell, L., The Pathological Effects of Radiant Energy on the Eye, Proc. Amer. Acad. Arts & Sciences, 5: 629-818, 1916.

2-427. Vinz, F. L., Knighton, M. H., Lahser, H. F., et al., Visual Simulation Facility for Evaluation of Lunar Surface Roving Vehicles, NASA-TN-D-4276, Feb. 1968.

2-428. Volkmann, J., Corbin, H. H., Further Experiments on the Range of Visual Search, ESD-TDR-65-169, Electronic Systems Div., L. G. Hanscom Field, Bedford, Mass., 1965. (AD-622414).

2-429. Volkmann, J., Corbin, H. H., Eddy, N. B., et al, The Range of Visual Search, ESD-TDR-64-535, Electronic Systems Div., L. G. Hanscom Field, Bedford, Mass., 1964.

2-430. Vos, J. J., Some Considerations on Eye Hazards with Lasers, TDCK-46027, National Defence Research Council, T. N. O., Medical Biological Lab., Rijswijk, Netherlands, 1966.

2-431. Vos, J. J., Theory of Retinal Burns, Bull. Math. Biophysics, 24: 115-128, 1962.

2-432. Wald, G., Alleged Effects of the Near Ultraviolet On Human Vision, J. Opt. Soc. Amer., 42: 171, 1952.

2-433. Wald, G., Human Vision and the Spectrum, Science, 101(2635): 653-658, June 1945.

2-434. Walls, G. L., Factors in Human Visual Resolution, J. Opt. Soc. Amer., 33: 487-505, Sept. 1943.

2-435. Walraven, P. L., On the Mechanism of Color Vision, Report Institute for Perception RVO-TNO, Soesterberg, The Netherlands, 1962.

2-436. Walsh, T. M., Warner, D. N., Jr., Davis, M. B., The Effects of a Gemini Left-Hand Window on Experiments Requiring Accuracy in Sighting or Resolution, NASA-TN-D-3669, 1966.

2-437. Watkins, W. H., Feehrer, C. E., Investigations of Acoustic Effects upon Visual Signal Detection, ESD-TR-64-557, Electronic Systems Div., L. G. Hanscom Field, Bedford, Mass., 1964.

2-438. Weasner, M. H., Carlock, J., Detection and Identification of Colored Smoke, Human Factors, 8(5): 457-462, Oct. 1966.

2-439. Wertheim, T., Uber die Indirekte Sehscharfe, Z. Psychol., 7: 172-187, 1894.

2-440. Westheimer, G., Drugs and Eye Movement Responses in Man, Recent Developments in Vision Research, Whitcomb, M. A., (ed.), NAS-NRC-1272, National Academy of Sciences - National Res. Council, Washington, D. C., 1966, pp. 215.

2-441. White, C. T., Ford, A., Eye Movements during Simulated Radar Search, J. Opt. Soc. Amer., 50: 909-913, 1960.

2-442. White, W. J., Acceleration and Vision, WADC-TR-58-333, Wright Air Development Center, Wright-Patterson AFB, Ohio, 1958.

2-443. White, W. J., The Effects of Transient Weightlessness on Brightness Discrimination, AMRL-TDR-64-12, Aerospace Medical Research Labs., Wright-Patterson AFB, Ohio, Mar. 1964.

2-444. White, W. J., Riley, M. B., Effects of Positive Acceleration on the Relation Between Illumination and Instrument Reading, WADC-TR-58-322, Wright Air Development Center, Wright-Patterson AFB, Ohio, 1958. (AD-206663).

2-445. White, W. J., Sauer, S. C., Scale Design for Reading at Low Brightness, WADC-TR-53-464, Wright Air Development Center, Wright-Patterson AFB, Ohio, 1954.

2-446. White, W. J., Vision, in Bioastronautics Data Book, Webb, P., (ed.), NASA-SP-3006, 1964, pp. 307-341.

2-447. Whiteside, T. C. D., Dazzle from Nuclear Weapons. Vision Research Reports, NAS-NRC-835, National Academy of Sciences - National Res. Council, Washington, D. C., 1960, pp. 79-96.

2-448. Whiteside, T. C. D., The Problems of Vision in Flight at High Altitudes, Butterworth, London, 1957, pp. 30-33, 42-55, 89-92, 105-113.

2-449. Whiteside, T. C. D., Visual Perception of Movement, Ann. Roy. Coll. Surg. Eng., 33: 267-281, 1963.

2-450. Wienke, R. E., The Effect of Flash Distribution and Illumination Level upon the Detection of Low Intensity Light Stimuli, Human Factors, 6: 305-311, June 1964.

2-451. Wilcox, W. W., The Basis of the Dependence of Visual Acuity on Illumination, Proc. Nat. Acad. Sci., 18: 47-57, 1932.

2-452. Williams, A. C., Jr., Simon, C. W., Haugen, R., et al., Operator Performance in Strike Reconnaissance, WADD-TR-60-521, Wright Air Development Center, Wright-Patterson AFB, Ohio, 1960.

2-453. Williams, L. G., A Study of Visual Search Using Eye Movement Recordings, Rep. 12009-IR-1, Honeywell, Inc., St. Paul, Minn., 1966. (AD-629624).

2-454. Williams, L. G., A Study of Visual Search Using Eye Movement Recordings, Rep 12009-IR-3, Systems and Research Center, Honeywell, Inc., St. Paul, Minn., Mar. 1967.

2-455. Williams, L. G., Target Conspicuity and Visual Search, Human Factors, 8(1): 80-92, 1966.

2-456. Williams, L. G., Visual Search: Eye Fixations as Determined by Instructed Target Characteristics, Rep-T-125, Honeywell, Inc., St. Paul, Minn., 1965. (AD-620336).

2-457. Williams, S. B., Visibility on Radar Scopes, in A Survey Report on Human Factors in Undersea Warfare, Committee on Undersea Warfare, National Research Council, Washington, D. C., 1949.

2-458. Williams, T. P., Photoreversal of Rhodopsin Bleaching, J. Gen. Physiol., 47: 679-689, 1964.

2-459. Willstrop, R. V., Absolute Measures of Stellar Radiation, Part II, Mem. Roy. Astron. Soc., 69: 83-143, 1965.

2-460. Wilson, R. C., Canfield, A. A., The Effects of Increased Positive Radial Acceleration upon Pupillary Response, in Psychological Research on the Human Centrifuge: Final Report, Warren, N. D., Bryan, D. L., Wilmorth, N. E., et al., N6-ori-77, Task Order 3, Dept. of Psychology, Univ. of Southern California, Los Angeles, Calif., 1951.

2-461. Woodhull, J. G., Bauerschmidt, D. K., Human Perception of Line-of-Sight Rates, HAC-2732.20/135, Hughes Aircraft Co., Culver City, Calif., 1962.

2-462. Wulfeck, J. W., Weisz, A., Raben, M. W., et al., Vision in Military Aviation, WADC-TR-58-399, Wright Air Development Center, Wright-Patterson AFB, Ohio, 1958. (AD-207780).

2-463. Young, L. R., Zuber, B. L., Stark, L., Visual and Control Aspects of Saccadic Eye Movements, NASA-CR-564, 1966.

2-464. Zaret, M. M., Ripps, H., Siegel, I. M., et al., Laser Photocoagulation of the Eye, Arch. Ophth., 69: 97-104, 1963.

2-465. Zaret, M. M., Grosof, G., Ocular Hazards of Laser Radiation, AMRL-TDR-63-132, Aerospace Medical Res. Labs., Wright-Patterson AFB, Ohio, 1963.

2-466. Zaret, M. M., Ophthalmological Effects of Intense Light Beams, AL-TDR-64-217, Air Force Avionics Lab., Wright-Patterson AFB, Ohio, 1965. (AD-468093).

2-467. Zuercher, J. D., The Effects of Extraneous Stimulation on Vigilance, Human Factors, 7: 101-105, 1965.