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VISUAL SENSING OF SPACECRAFT GUIDANCE INFORMATION

Earth Orbit Rendezvous Maneuvers

by S. Seidenstein, W. K. Kincaid, Jr., G. L. Kreezer, and D. H. Utter

Prepared by
LOCKHEED MISSILES & SPACE CO.
Sunnyvale, Calif.
for Langley Research Center

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SUMMARY

An analysis of earth orbit rendezvous in terms of maneuver geometry served as a basis for establishing the requirements for visually sensed rendezvous guidance information. Analysis of the physical environment supported an evaluation of the sensory basis for visually deriving the desired information. Visual capabilities were then examined in terms of sensitivity, cross range motion perception, range, and range rate determinations. Estimates of sensitivity and variability are presented where available. Conclusions are drawn regarding the adequacy of available data, and recommendations are given for future areas of study.

INTRODUCTION

This report is intended as a source and a guide for applying information concerning human visual perception to the sensing of guidance and control information in manned spaceflight. Its purpose and plan is as follows:

- define the basic visual stimulus conditions applicable to spaceflight;
- review relevant operational tasks and define the visual/perceptual and physical phenomena related to each;
- define the parameters to be investigated in terms of perceptual capabilities;
- review the literature for related studies and experiments to compile pertinent data;

- produce a data summary;
- outline a program of analysis and experimentation to provide data not found in the literature.

Rendezvous has been chosen as the operation for which information is required. Rendezvous guidance and control schemes have been studied in order to establish the parameters which must, or could be sensed. Parametric limits have been defined. The physical characteristics of the space vehicle and its natural environment are defined, quantified, and related to one another in order to describe the stimulus environment from which visual information is sensed.

Certain characteristics of the visual system are also examined where they might modify the sensing capability. These analyses culminated in the question, "What data exist to quantify the capability of the human to sense the desired information?" The literature has been reviewed and evaluated in an attempt to answer this question, or to assess the extent to which it can be answered.

Since the areas investigated are highly selective, and the available literature frequently inadequate, the scope of this work is necessarily limited. Because we consider the results of our efforts to be a working tool for assisting individuals whose technical specialty is not vision, we have included a number of generally available references where a broader understanding of visual perception may be obtained, where detailed descriptions of methods and procedures are available, and where supplementary data exist. Since the largest portion of the available data was generated to fill the goals of a basic understanding of the visual system, it is frequently obtained under conditions which are difficult to generalize to the operational situation. For this reason we have included a brief discussion on methods and procedures which we hope will alert the user to some of the hazards inherent in not questioning the utilization of summary data.

In performing this analysis we have attempted to obtain quantitative relationships where possible, and have probably neglected certain phenomena which very real, cannot be readily treated in the quantitative framework.

We have drawn heavily upon secondary sources in compiling data and figures in part due to availability, and in part due to limitations of time. These secondary sources are readily available to the reader who wishes to extend his analysis beyond the data presented herein.

This study was conducted under the general supervision of Dr. S. Seidenstein who was responsible for the sections on visual sensitivity and cross-range motion. W. K. Kincaid Jr. contributed the section on physical environment, Dr. G. L. Kreezer, the section on range and range rate determinations, and D. H. Utter the section of rendezvous mission and guidance requirements. C. S. Juliano contributed the material on visual aids. Technical guidance and support were expertly provided by Dr. R. L. Martindale and V. E. Jones, Jr.

RENDEZVOUS MISSION AND GUIDANCE REQUIREMENTS ANALYSIS

This investigation was begun by determining what information would be required to perform a rendezvous.

An analysis of the rendezvous mission and guidance information requirements was conducted concentrating on the following areas:

(1) A literature search of both manual and automatic techniques for accomplishment of space rendezvous.

(2) Compilation of a list of rendezvous mission phases (by function).

(3) Compilation of a list of guidance schemes under each mission phase.

(4) Selection of two guidance schemes for further study.

(5) Collection (for each guidance scheme selected) of mission geometry, parameters required, ranges of parameters, visual references, and techniques for obtaining data.

Rendezvous Mission Phases

The overall rendezvous mission may be broken down into functional phases. Each of these phases is a necessary part of a typical rendezvous mission and usually represents one of a sequence. The following phases were considered:

(1) Target search and acquisition.
(2) State (relative position and velocity) determination.
(3) Initial state correction.
(4) Transfer path control.
(5) Final velocity correction (braking).
(6) Stationkeeping.
(7) Near target maneuvers.
(8) Docking.

Mission Phase and Guidance Schemes

The guidance schemes applicable to each mission phase are listed below:

	Mission Phase	Guidance Scheme
I.	Target search	--
II.	State determination	A. Earth orbit mechanics B. Relative orbit mechanics * C. Inertial line of sight (L-O-S) collision course
III.	Initial correction	A. Minimum impulse * B. Inertial L-O-S collision course * C. Rotating L-O-S collision course
IV.	Path Control	A. Uncontrolled * B. Inertial L-O-S collision course * C. Rotating L-O-S collision course
V.	Final braking	A. Minimum impulse * B. L-O-S range programmed range-rate
VI.	Stationkeeping	* A. Rotating L-O-S
VII.	Near target maneuvers	--
VIII.	Docking	--

Mission phases I, VII, and VIII, included for completeness, are considered beyond the scope of the rendezvous mission as defined for purposes of this study.

The guidance schemes selected for further study as appropriate to potential visual implementation (listed above) fall into two general schemes:

(1) Inertial line-of-sight collision course,

(2) Rotating line-of-sight collision course.

The mission geometry is nearly the same for both guidance schemes. Each scheme uses the target vehicle orbit as the reference orbit. Each scheme uses equations, describing the relative motion of the chaser vehicle with respect to the target, in spherical coordinates referenced to a set of axes centered on the target. However, scheme #1 utilizes an inertially fixed set of reference axes while the axes of scheme #2 are aligned to the local vertical. Figures 1 and 2 illustrate the geometry of the two reference systems.

Both guidance schemes require use of the same spherical coordinate parameters: range, R, elevation angle, α , azimuth angle, β , and their rates. The inertial guidance scheme requires α measured with respect to an inertial reference, while the rotating scheme requires α measured with respect to the local horizontal at the target. The range of these parameters is given in Table I.

The equations of relative motion for each guidance scheme as given by Harrison (ref. 20) are repeated in Table II.

Visual References and Techniques for Obtaining Parameters

For the inertially based reference scheme (scheme #1) the visual references will be two stars: one located at or near the target vehicle, the second located in the target orbit plane. For the rotating reference scheme (scheme #2) the visual references will be the earth horizon and one star to locate the target orbit plane.

An examination of the references revealed several techniques for obtaining the required guidance parameters: R, α , β , and their rates. These techniques are listed in Table III.

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PHYSICAL CHARACTERISTICS OF THE VISUAL ENVIRONMENT

Introduction

The physical environment of space is a major determinant of an astronaut's visual capabilities. The ability to visually acquire and track a target vehicle throughout a rendezvous mission as well as make navigational sightings occurs within a multiparameter physical environment which in part determines maximum visual performance capabilities. These parameters can be considered under a number of logically separable groupings:

Orbit position. - The number and types of objects, both luminous and illuminated, which can appear in the astronaut's field of view through either the spacecraft window or optical instruments are determined by the spacecraft's orbital position. The important angular and line of sight relationships between the chase vehicle, search vehicle, and sources of illumination are similarly determined.

External brightness field. - The special nature of the space environment, e.g., the lack of any atmosphere, the intensity and special characteristics of the natural illumination sources, and the number and types of objects external to the spacecraft and within the field of view determine the average brightness of the astronaut's external viewing field.

Luminous objects such as the sun and stars and illuminated objects such as the moon, the earth, and the spacecraft "corona" (a cloud of spacecraft ejected particles which are trapped by the spacecraft's electrostatic and gravitational fields) are at one time or another found in this field of view.

Target vehicle characteristics. - Characteristics such as target size, shape, specularity, and orientation, when combined with a knowledge of the illuminance source and the target distance provide necessary data for the analysis of the "effective target" brightness and target contrasts. In the case of earth nightside activities, the characteristics of target acquisition beacons and, for close-in operations, the target's colored running lights must also be considered.

Spacecraft windows and/or optical devices. - These light transmitting "media" are filters through which the astronaut observes the external field and the objects within that field. They contribute to increased homogeneity of the visual field by scattering light within themselves. They act either as neutral density or selective spectral bandpass filters. The properties of optical devices affect the apparent brightness of the targets, their backgrounds, and the angular size of the field of view.

Spacecraft internal lighting. - Internal spacecraft lighting, along with the external light entering through the spacecraft windows, creates the total "effective" brightness field for the astronaut-observer.

The eye as a sensor. - The sensitivity of the eye is an important parameter. The eye is only able to detect an object which differs sufficiently in brightness from the surrounding field. Sensitivity is a function of adaptation, which is in turn a function of the spatial and temporal characteristics of the prevailing field brightness. Considerable data exists which indicates the minimum differential object brightness which can be detected by an eye adapted to a particular surround.

The interrelationships between the various parameters discussed above are presented schematically in Figure 4.

Orbit Related Characteristics

The purpose of this section is to describe the physical environment of space as it operates to determine the visual performance of the astronaut observer.

Orbit position. - Initially, the orbital position establishes the number and types of possible sources of illumination, as well as certain basic angular relationships such as the angle between the incoming target illumination and the line of sight. Figure 5 is a diagram indicating the various illumination environments which might be encountered by a vehicle in the Earth-Moon space.

In general, the brightness of a surface which reflects light is a function of the area of the surface, the light incident on the surface, the percent reflectance, and nature of reflectance, whether spectral or diffuse. This relationship is confined to angles in the range of 0^{o} - 180^{o} depending upon the relative position of the light source(s), and target and chaser vehicles as defined by the orbital position of the vehicles.

If the sun is regarded as the major source of target illumination, there are certain unique characteristics of sunlight which must be considered.

Since the earth-sun (or moon-sun) distance is so great, the light rays emanating from points on the sun's surface are essentially parallel when they reach the earth, moon, or any point between the earth and the moon. Another result of the great distances involved is the apparent uniformity of illumination on a plane oriented at any angle to the incident sunlight. The variation on intensity over these planes is well below the brightness discrimination threshold (ref. 9). For this reason, it is generally assumed that the incident illuminating sunlight intensity is 100% uniform over the illuminated surfaces which are observed by the astronaut regardless of the sunlight incidence angle or size of the illuminated area. This illuminating intensity is termed the solar constant (Eo) and is equal to $1.25(10)^{4}$ ft-candles at the earth-sun distance. The only spread (decollimation) which is encountered is that due to the angular size of the sun ($\sim$ 32 minutes of arc) as viewed from the earth-sun distance.

Earth orbit parameters also determine the maximum possible straight line target sightings over the horizon. For example, a space vehicle at a 100 n.m. altitude has a maximum possible straight line sighting distance to a target at the same altitude (and in the same circular orbit) of about 730 n.m. On the other hand, if both chaser vehicle and target were in the same 500 n.m. altitude, circular orbits, the maximum possible sighting distance would be about 3750 n.m. In these calculations, 20 n.m. was added to earth radius to account for the earth atmospheric "aura."

The amount of time spent by spacecraft in the dark or light is a function of the orbit characteristics. If, for instance, only sunlight is considered, spacecraft in circular or only slightly elliptical equatorial orbits of 100 n.m. and 500 n.m. altitudes are in the Earth's shadow about 37 and 38.5 minutes, respectively. For an ellipticity of as great as 0.113, with the perigee on the sunlit side at a 100 n.m. altitude; a similar analysis indicates that the time spent on the dark side in an equatorial orbit is still only about 37 minutes. It is apparent that for most earth orbit missions the time in darkness will be about 37-38 minutes. If moonlight is available on the dark side of the Earth, its effect on the dark adaptation level must also be taken into account. It has been stated by the astronauts that under full moonlight conditions on the dark side of the Earth, it is possible to read within the spacecraft using only the light from the moon (ref. 1). This suggests a minimum luminance level within the spacecraft of 10^{-2} ft.Lamberts which is quite high compared to the darkness of space sky. In Table IV, the brightness of various combinations of "natural" field objects and backgrounds are given.

Figure 6 schematically indicates the geometry involved in the analysis discussed above and gives an expression for the approximate amount of time spent in sunlight and earth darkness for the spacecraft at various altitudes in circular, equatorial earth orbits. An expression for the maximum line of sight distance between two spacecraft at about the same orbital altitude is also given.

External field objects. - It is assumed that at all times the astronaut's field of view through the spacecraft windows will contain light sources such as stars, sun, moon, earth, or combinations of these objects. Except for the stars, all of the objects should always be above the threshold or lower limit of eye sensitivity except when the sun is within the field of view or incident on the spacecraft windows or optics. The brightness of stars are conventionally given in stellar magnitudes. The stellar magnitude is actually a measure of the earth based reading of the illuminance provided by a given star. For a star whose usual magnitude is one, the illuminance is given as 9.73×10^{-8} footcandles (ref. 29). Note that each of the stellar magnitudes shown in Table V vary in illuminance steps, ΔE, by the factor 2.5119.

To convert the illuminance at a given point provided by either a star or any other source of light into stellar magnitudes at the earth's surface, the following expression can be used:

$$m = -2.5 \log E - 16.53, \qquad \text{(ref. 1)}$$

where,

m = stellar magnitude (at the earth's surface)

E = Illuminance (footcandles)

It may be useful to remember that the stars are in the astronaut's external field of view in the daytime but the light adapted eye is too insensitive to detect them (ref. 11). If they are to be used as navigational aids and reference points against which a target vehicle is distinguishable by its line-of-sight angular rate, they must be visible. The distribution of stars with respect to brightnesses and density exhibits such variability that it is not useful to specify average values over specific short time period for a given orbit. It is possible, however, to establish the relative mean of the less dense and less bright portions of the sky. These are the more important values since they establish the extremes. Figure 7 represents star density as a function of magnitude (mean) for several angular field sizes (ref. 24). This information, combined with adaptation level and the properties of the optics determines the number of stars which are visible for a given field size.

Target-background contrast. - In situations where the target must be viewed against the sunlit Earth's surface, or where stars must be viewed near a bright object such as the sunlit Earth's horizon, the moon or a sunlit target vehicle, the contrast ratio between the target or star and its background must be used in the calculations of visibility. The contrast ratio most frequently used is given as:

$$C = \frac{B_t - B}{B} \times 100$$

where B_t is the target brightness and B is the background brightness.

Values of background brightness for sunlit and moonlit earth background and earth airglow background are given in Table IV.

Figure 8 is a plot of minimum visible angular size of a circular target as a function of the contrast ratio and the background luminance. It can be used to obtain first approximation values of detection range if contrast ratio (C), background luminance and vehicle size are known. The original data from which this curve was plotted is that obtained by Blackwell (ref. 2). A very extensive set of data considering targets, up to 6° of arc, is given by Duntley (ref. 8).

Glare. - "Glare" as discussed below is the effect of stray light from sources much brighter than the target object which tend to "veil" the visual field by superimposing their brightness over the line of sight field of view.

The quantitative effects of glare are not fully known. Research, such as that being conducted by Dr. Richard Haines at Ames Research Center, is attempting to quantitatively describe the effects of extended glare sources on the visibility of objects near the glare source. The expression empirically derived from experimental data for "veiling" illuminance, E_V, when the eye is fixated on a point Θ degrees from a steady light source which provides E footcandles of illumination at the eye, is

$$E_V = 10(E)/\Theta_V = \text{foot candles.} \qquad \text{(ref. 13)}$$

The Gemini astronauts reported difficulty in making sightings on stars near the edge of the sunlit lunar disc, which is, in this case, the result of the glare effect (ref. 25).

Corona. - Since a spacecraft ejects particles of fluid which remain near the vehicle because of electrostatic and to some extent gravitational fields, it creates and transports its own source of light scatter or "corona". This corona tends to decrease the contrast ratio between the vehicle and the surround. Figure 9 illustrates the brightness of such a corona as a function of the mass ejection rate. Mass ejection rates of approximately 1 lb/hr are typical of those encountered during the Gemini flights (ref. 12). Those for the Apollo vehicles will certainly be higher, but typical values are not, at present, available.

Target Vehicle Characteristics

Point source or extended source. - In a typical rendezvous, the target vehicle initially appears at a distance where it can be treated as a point source. Because of its small subtended visual angle, the target vehicle obeys Ricco's law, Area x Intensity = Constant, for an effective "point" source (ref. 29). Thus, a "point source" may be defined in practical terms as a stimulus which "affects the eye only in proportion to its intensity" (ref. 21). Figure 10 taken from Blackwell (1946) shows the critical visual angle below which a source may be treated as a point. This in turn is a function of the size of the aperture of the pupil and as such is a function of the average luminance of the field of view. This is discussed further on page 38.

For the dark adapted eye the upper limit is generally given as eight minutes of arc while for the light adapted eye the upper limit is about 0.5 minutes of arc (ref. 23). Figure 11 presents the minimum range beyond which a circular target can be considered as a point source for various circular target diameters and for both the dark adapted and light adapted eyes. The direct variation of pupil size with the luminance of the field of view is shown in Figure 20 . The pupil area varies by approximately the same factor (16) as the ratio of the maximum angular sizes of point sources for the light and the dark adapted eye. If the source can be treated as a point, the inverse square law (illuminance to a point (p) is inversely proportional to the square of the distance from p to the point source) is valid.

For vehicles where the combination of target angular size and pupillary size indicate a source is too large to be considered a "point" (see Figure 10), the inverse square law is no longer valid for the entire source and the target is considered an "extended" source or a sum of point sources. The intensity must then be considered in conjunction with the illuminated area of the source and the angle formed between the line of sight and the normal to the surface for each point in order to obtain target brightness. If it is not possible to regard the target vehicle as a point source, the illumination at the eye must be found by either calculating the total flux entering the eye and dividing by the area or by averaging the illumination at each point of the pupil over its area. As an example of the difference between the expressions for illumination at the eye for point sources and extended sources, consider a flat disc having a diffuse reflecting surface. For the case where the disc appears as a point source, the illuminance at the eye E (for a zero angle between the line of sight and the incident illumination) is given by the inverse square law as I/D^2, where, I, is the normal luminous intensity of the disc and, D, is the distance from the eye to the disc. For the extended source, the illuminance, E_h, becomes $I/(D^2 + r^2)$ where, r, is the radius of the disc. It can be seen that the illuminance is an explicit function of the size of the source for extended source targets. If a one (1) percent difference is allowed between the illumination calculated using the point source equation and the extended source expression, i.e., $D^2/(D^2 + r^2) = 0.99$, the distance to radius ratio is about 10. The angle subtended by the disc diameter in this case is about 11°. This means that if this one (1) percent difference is allowable, a target could be as large as 11° and the inverse square law would still be valid in calculating the illuminance at the eye (ref. 11). The diffusely reflecting surface was used in this case in order to simplify the expression and the analysis. In the case of a diffusely reflecting disc illuminance is independent of the viewing angle.

Target geometry. - Even though a target appears to the eye as a point its actual physical characteristics must be considered in detail in order to specify how much light energy this point will reflect in any given direction. All of the space vehicles are made up of one or more of the basic geometric shapes; i.e., discs or flat surfaces, spheres, cylinders or cones. Table VI indicates the brightness of each shape and the illumination at an observer's eye as a function of illumination incidence angle and viewing angle. The brightness expressions (B_a), for the extended sources are for equivalent flat surfaces and a discrete case about the x-axis. This brightness approximation for the geometric solids is generally valid (depending on target size) for ranges down to one or two miles, where the object is no longer treated as a point and may be perceived as extended or three dimensional. It can be seen that the cases presented provide brightness and illuminance for fairly general in-space lighting situations. Figures 12 through 19 present the results of calculations using the equations in Table VI.

The maximum target vehicle size (20 ft. diameter x 100 ft. in length) used in these figures was approximately that of the docked CSM and SIVB configuration. However, in order to indicate the effect of size on trends in target brightness, sizes smaller than this maximum were included in the analysis. If target vehicle sizes larger than the docked CSM-SIVB are encountered, the data presented will provide a basis for extrapolation.

It might be noted that each of the equations presented in Table VI are amenable to an error analysis. The result of such an analysis would be to establish the sensitivity of the resulting illuminance to each of the parameters involved in the expressions. This may be useful in planning mission operations and procedures. If changes in one or more of the parameters have little effect on the resulting value of luminance, it might be possible to estimate range, for instance, using brightness comparison techniques without knowing the exact values of certain target vehicle characteristics. As an example, errors introduced by inaccuracy in estimating vehicle size may not introduce significant errors in a judgment of distance based on changing brightness. A complete analysis is not possible within the scope of this study, but it is an area of possible further interest.

Target surface characteristics. - The intensity of an illuminated target is directly proportional to its reflectance or albedo and the specularity of its surface. Reflectance is generally defined as the percentage of light which is reflected by the surface and, except for a few isolated types of materials, is independent of the wavelength and angle of incidence of the illuminating rays. Specularity can be considered as the amount of surface roughness or a measure of the deviation from tangency of a microscopic "facet" of the surface with respect to the average slope of the surface.

Bouguer presents an analysis of these relationships (ref. 4) for a sphere. He assumes the surface to be covered with small mirrors whose deviation from tangency with the slope of the surface is some Gaussian distribution function. The results of that study were restricted to a specific angle of incidence of the illuminating rays and a specific viewing angle. They did, however, indicate a marked variation in the intensity per unit area of the target as a function of the specularity and the point on the target's surface which was being examined. The total energy reflected to a given point by the surface was not evaluated. Since there was such a large variation in the intensity per unit area, as a function of the variables mentioned above, a further analysis using a more general approach would be helpful in choosing the target surface coating and shape. This coating could be chosen to satisfy the requirements for target visibility at long range; i.e., rendezvous and guidance information, and those for size and shape perception which occur in the docking phase of a mission. It has not been ascertained that either a diffuse or a specular surface completely satisfies either of these requirements.

During docking and close-in inspection of a target, it is quite difficult to perceive the shape geometry of a specular surface illuminated by collimated sunlight (ref. 18). Since diffuse surfaces reflect impinging rays back in many directions some sunlight directed back toward the observer from all points of the illuminated surface will enter the pupil. For Specularly reflecting surfaces, only those rays of light which have the appropriate incidence angles will be reflected in the directions required for entering the pupil of an observer's eye (see Figure 11). Thus portions of a spacecraft may be effectively invisible or their presence recognized only because they are silhouetted against known or surmised visible objects in the field of view.

One Gemini astronaut reports the group requested that rendezvous targets be either coated with a diffuse, preferably white material or at least have portions of the surface covered with stripes which are diffusely reflecting. This facilitates perception of shape-geometry, close-in distance judgment and recognition of target attitude.

Table VII describes characteristics of some of the surface coatings presently being considered for portions of the Apollo mission vehicles as well as those used during the Gemini - Agena missions.

Target vehicle lights. - Running lights are to be used on the Apollo mission vehicles, as they were on Gemini, to assist the astronauts in judging target vehicle attitude during Earth nightside activities.

Table VIII presents the colors and intensity outputs of the various types of running lights being used. During the Gemini IX mission, astronaut Cernan stated that he was able to perceive the red running light on the Augmented Target Docking Adapter (ATDA) at a maximum distance of 8 n.m. while backing away. He also stated that while approaching the target from a range of five miles, the running lights could be seen in the following order: red, amber, green. These facts seem to indicate the possible use of recognition of running light colors as a source of gross range or range rate information since the colors seem to be discriminable as a function of range. The basis for this may be understood from a curve showing the relative sensitivity of the light adapted eye to various wavelengths in the visible spectrum (Figure 21).

Acquisition beacons. - In the Gemini rendezvous missions and the proposed Apollo missions a flashing Xenon beacon was, and is to be the acquisition light. An acquisition beacon facilitates visual detection of the target when both chaser and target are in the Earth's shadow. Table IX presents the intensities for beacons used on Gemini flights and those which are presently proposed for use during the Apollo missions. The values given in this table are those measured in the direction of maximum beacon output and include the brightness effect due to the Blondel-Rey factor (ref. 3). It must be noted that, due to asymmetry in the lamp output, beacon intensity varies with the direction from which it is viewed. whether flashing or steady. A curve showing the typical variation of intensity with viewing angle is given in Figure 22. The beacon intensity is given in beam candle power seconds (i.e., $I_f t_p$, see below), and as such the Blondel-Rey factor effect is not apparent in the light output presented in this figure. The threshold intensity of flashing lights is increased over that of a steady light in a manner described by the following expression:

$$I = \frac{I_f \, t_p}{t_p + a}$$

In this expression, I = steady source intensity

I_f = flashing source intensity required to appear as bright as I_s

t_p = flash duration

a = Blondel-Rey factor $\sim$ 0.21 seconds

Our experience has shown that the equation above can be easily misunderstood. This expression does not state that the flashing light has a higher apparent brightness than a steady source. Rather, it makes the opposite statement, i.e., that if a flashing light is to appear as bright as a steady source, it must have a peak intensity which is greater than that of the steady source. As the flash duration decreases, the flash intensity required to appear as bright as a given steady source intensity increases. A common error occurs when the expression is written in the form:

$$\frac{I_f}{I} = \frac{t_p + a}{t_p} .$$

This form seems to indicate that the flashing light intensity must always appear to be greater than the steady source when in actuality it states that <u>in order to</u> appear as bright as the steady source, the flashing source must be greater (see Figure 23).

For flash intensities above the visual threshold, the expression is that arrived at by Hampton (ref. 11):

$$E_f = \frac{E}{t_p}\left[\frac{(.0098)}{E}^{0.81} + t_p\right]$$

where, E_f = Illumination at the eye (flashing source) in lumens/square kilometer

E = Illumination at the eye (steady source) in lumens/square kilometer

Flashing lamps are rated in candle-seconds which, in regard to the expression above, indicates that if the flash duration (t_p) is short (on the order of .001 sec) the product of the flash intensity and duration is increased by the factor, 1/a.

Spacecraft Characteristics

<u>Optical media</u>. - The spacecraft window is the primary optical medium through which the astronaut views the target vehicle. Table X presents the characteristics for the Gemini, Apollo CM and LM windows. Included in this table are the field of view angular size, visible light transmission for the

"clean" window and percent scatter.

All of the data for percent transmission and scatter is optimistic since it represents pre-flight measurements. It was shown in post-flight measurements on the Gemini and unmanned Apollo windows that they tend to become coated, resulting in a progressive degradation in light transmission and resolution. This same result has also been noticed in the SC-002, SC-009, and to a lesser degree in the SC-011 Apollo CM flights. Post-flight measurements made on Gemini and the first unmanned Apollo flights indicate that at best, window transmission is 75-80 percent and on Gemini 5, a window transmission of 20-25 percent through a highly contaminated area was measured. Since these were post-flight measurements and the effects of re-entry on the amount of contamination is not known, they must only be considered as qualitative results. Although the astronauts have stated that the windows were "dirty" during the orbit phase of the Gemini missions, no quantitative transmission data was obtained during the flights. Transmission losses are of importance, but it must be realized that a decrease in transmission to as little as 40 percent only decreases the visible stellar magnitudes by about one (1). The more important effect is the increase in light scattered in the contaminant layer. This tends to "veil" the visual field by decreasing the contrast ratio between the target vehicle and its background.

In the first Gemini flight which used an acquisition beacon, visual acquisition range was 12 n.m. which was less than its specified detection range of 20 n.m. As can be seen from Table IX, the output of later beacons was increased; primarily to alleviate this problem. Studies initiated during the time period in which the beacon output was increased, indicated that the veiling luminance, resulting in decreased contrast, in the spacecraft windows and the ambient internal lighting levels caused the decrease in sighting range from that originally specified. When the beacon was considered as a target against the illuminated window the data were similar to those obtained by Blackwell (ref. 2) for contrast thresholds.

The window provides an adaptation field for the astronaut which is independent of the spacecraft internal lighting when sunlight or earthlight illuminates the window. For nightside operations, external light levels are too low to produce light scatter in the windows and except for internal reflections, which are minimized by special coatings, windows do not degrade visibility beyond that caused by the contaminants.

The Apollo alignment optical telescope (AOT) is installed in the lunar excursion module (LM) and is used for aligning the inertial guidance system. In the Apollo Command Module a combination scanning telescope and sextant is installed for use in obtaining guidance and navigation information. Table XI presents the optical characteristics of each of these instruments.

When an optical device is used by the astronaut for visual acquisition of a target, the optical gain must be considered. Optical gain in the case of a point source which remains a point source after magnification operates only to increase its apparent brightness. This is because, by definition, the point source apparent brightness remains a function of source intensity and not a function of its area as distance is decreased. In the case of an extended source, the optical gain operates to provide linear magnification as well as an apparent intensity increase. The combination of these tend to nullify each other as is demonstrated by the following equation:

$$\text{Optical Gain} = G = \frac{TD_i^2}{D_o^2 M_\ell^2} \qquad \text{(ref. 8)}$$

where, if $D_o > \dfrac{D_i}{M_\ell}$

T = optical transmission

D_i = objective diameter

D_o = natural eye pupil diameter when observer is adapted to the true background brightness without the instrument

M_ℓ = linear magnification

If the target vehicle still appears as a point source after magnification, the gain is given as:

$$G = \frac{TD_i^2}{D_o^2} \qquad \text{(ref. 8)}$$

<u>Spacecraft internal lighting.</u> - The luminance levels within space-

craft are variable, from a maximum of about 10-20 foot Lamberts to a lower level of about 10^{-3} foot Lamberts. Figure 24 shows the photometric measurements taken within the Gemini V spacecraft during a daylight portion of the flight. These values are quite high when compared to those in Figure 25, which were measured in a post-flight re-creation of the in-flight nightside internal lighting levels. In the early Gemini flights, there was no concerted effort on the part of the astronauts to dark adapt prior to visual acquisition of target vehicles. Their visual sensitivity was determined largely by internal cabin luminance. Thus, detection ranges were less than were originally predicted. On later flights (VIII-XII) an effort was made to decrease the spacecraft internal lighting to its minimum values at least on the command pilot's side and a rather obvious performance increase was noted (see Figure 26). In the case of Apollo, the illumination levels are to be of the same magnitude as those in Gemini. To maximize detection ranges the navigator's portion of the spacecraft must, therefore, be kept at the minimum level prior to his making sightings using direct optical means or the scanning telescope-sextant equipment. This is also true for the command pilot's area during visual rendezvous portions of the flight. A detachable "hood" or light shield would help to alleviate any adaptation problems by masking out the internal lighting required by one or more of the astronauts at all times in order to monitor instruments and perform various calculation and logging tasks.

Visual Sensitivity and the Physical Environment

"Effective" brightness field. - The previous discussion has been concerned primarily with the physical environment as it exists in space and not its effect on the eye; the exception being in the discussion of pupil size as it relates to division of targets into "point" sources and "extended" sources. All the factors discussed above must be assessed to determine a total "effective" brightness field or background of the visual environment. The ambient illuminance of the spacecraft cabin, the "surround" or background illuminance transmitted by the window and the illuminance of the target itself, all contribute to the "effective" brightness field.

Visual sensitivity. - Since the visual system basically adjusts its sensitivity gradually as a function of the amount of light energy received per unit time (see p. 42), this "effective" field establishes the adaptation luminance. This, in turn, defines the maximum sensitivity the eye can attain.

Figure 25 shows minimum target intensity required for detection as a function of the background luminance to which the astronaut is adapted. The range shown covers all of the probable visual situations which the astronauts would encounter. The equivalent stellar magnitudes (earth based observations) for a given threshold are presented in this figure.

A typical adaptation curve which indicates the threshold illumination at the eye as a function of the time in complete darkness is given in Figure 33. It can be used to establish the threshold levels which can be expected for astronauts after a given amount of time in darkness portions of an orbit.

A much more detailed discussion of visual sensitivity is given in the section beginning on p. 40.

Operational Flight Experience

In order to assess the usefulness of the analytical expressions and discussions presented in the preceding sections, an attempt has been made to combine the visual sighting information from several of the actual Gemini missions (GT-V through GT-IX) with the data produced here analytically. The mission reports yielded information such as the position in orbit with respect to the earth night-day terminator line, the sighting distance, the type of target vehicle involved, the source of illumination or luminance in the case of beacon sighting (see Table XII). In addition, information was presented for initial acquisition range and apparent stellar magnitude as well as for the apparent brightness of the target at various times subsequent to its initial sighting. Such parameters as window transmission and target reflectivity have been assigned typical values in order to facilitate the analysis. With this information, it is possible to calculate the illumination at the eye (E) using the expressions presented in Table VII. The threshold values can then be compared with the data presented in Figure 25, to obtain the background luminance under which a target of the calculated intensity would be perceptible. These background luminances have been compared with the typical background luminances presented in Table IV in order to establish the validity of the analysis. In all but two of the cases examined for the Gemini flight data, there was a close correlation between existing background luminance and those which the analyses predict. These results are presented graphically in Figure 26. It was not possible with the information available in the mission reports to completely and accurately reconstruct the chain of events leading up to the observations made by the astronauts but it is assumed that the levels of both the "questionable" points could be explained with more detailed information available.

Two distinct differences exist between the analytical results obtained from flights prior to GT-VIII and those for GT-VIII and the subsequent missions. By way of an explanation it is known that for all flights after GT-VI and GT-VII missions, the astronauts were instructed to make a concerted effort to dark adapt before visually searching for the target vehicle. This was accomplished by reducing the internal spacecraft illumination and the illumination of the boresight reticle to minimum levels on the command pilot's side of the cabin, using a handheld light shield in some cases and using only a minimum working illumination level on the pilot's side of the cabin. It can be seen that the data presented substantiates the value of this procedure since the adaptation level for missions after GT-VII was about one and a half log units lower than that experienced during GT-VII and earlier flights.

Approximations were used in the above analysis for vehicle shape. The ATDA, for instance, was assumed to be a diffusely reflecting white cone since the major portion of the attached cylindrical afterbody had a low reflectance coating. The Gemini adaptor section, its major source of reflected sunlight, was approximated as a cylinder, again with a diffusely reflecting white coating.

The derivation of this "adaptation" curve is typical of the types of analyses which may be accomplished using the physical environment parameters discussed in the preceding sections. It is possible not only to provide approximate values where they are missing, as in the analysis above, but also to use the approximate values which can be evaluated in order to provide hardware design specifications and operational procedures for existing hardware.

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MEASURING VISUAL CAPABILITIES

The eye is a sensor which normally responds to electromagnetic radiations in a specific region of the spectrum. These radiations, if of sufficient energy to excite the visual receptors are termed the adequate stimuli for the visual sense. Other forms of stimulation, such as a blow on the head, may lead to visual sensations such as the proverbial "seeing stars", but these are not the stimuli to which the receptor is designed to respond. The rich and complex world of sensation and perception can, to a certain degree, be analyzed in terms of relationship between relatively simple stimulus situations and the corresponding response of the organizm. These relationships can in many cases be treated quite precisely. The study of such relationships is generally termed psychophysics.

The conduct of experiments,the gathering of data, and the theoretical description of relationships between stimulus situations and the results they produce can be treated entirely on the basis of observable phenomena without any reference to concepts such as mind. Psychologists have waged many battles over whether psychology is, on the one hand, the study of the mental life of a person, or, on the other, the objective and repeatable observations of behavior, or a thousand intermediate positions. We shall find that many of the problems directly relevant to the applied situation can be treated without any reference to what the individual thinks, or to the concept of mind. While knowing that persons think is helpful in providing insights and suggestions regarding the processes underlying sensation and perception, the gathering of data and the establishment of relationships of primary interest in the applied situation can be based entirely upon observable behavior. Thus, a typical experiment might require an observer to press a button when he sees a certain stimulus. By presenting enough stimuli, using enough subjects, and gathering many such responses, consistent and reliable relationships can be repeatedly obtained.

The study of behavior is difficult, but not because the techniques are exceptionally difficult to master. Rather, the problem arises because behavior is multiply determined, and it is exceedingly difficult to isolate and control the variables which produce and modify specific behavior. This results in the use of experimental situations which are often highly idealized and quite simplified in order to reduce the variability which might be produced by an enriched stimulus environment. It leads to the use of large numbers of subjects in such carefully controlled experiments in order to reduce the variability which occurs as a function of differences among individuals. It leads to the use of elaborate statistics and experimental designs which permit one to control, randomly distribute, or analyze the effects of experimental treatments as well as factors such as practice, mptivation, etc. It leads to the use of statistical probability statements defining a relationship because, in spite of all efforts to do better, some variation not due to experimental manipulations still is present in the data derived. It leads, unfortunately, to an image of psychology as the study of white rats and college sophomores.

Here, another important point must be made. There is rarely a one to one relationship between the physical stimulus situation and the psychological response to that stimulus situation. An example which will probably be most familiar to the engineering community is that of the relationship in acoustics between the intensity of a sound and its loudness. Note that a distinction is made between the physical quantity, intensity, and the psychological quantity, loudness. The audio engineer is familiar with equal loudness contours which indicate that tones of various frequencies must be varied in intensity as much as 70 to 80 db to appear equally loud, and that the magnitude of the intensity change required varies as a function of the loudness level desired. Any good contemporary high fidelity system will have some means of adjusting loudness contour to compensate for this relationship.

Quite clearly, however, there are certain aspects of the physical wprld which, when systematically varied produce consistent though probably nonlinear changes in response. In sensory psychology when such a relationship exists between some simply defined stimulus dimension and a psychological dimension, we can speak of the physical situation as a "cue" to the psychological dimension. As will be seen in the discussion of distance perception, differences in the angular position of images on the retinae of the two eyes serve as one cue for depth or distance perception. The concept of cues is an extremely useful concept for our purposes, for it enables us to examine the physical environment and derive from it possible bases upon which the visual system could derive the desired guidance and control information. In actuality the individual rarely perceives a single psychological continuum in isolation, unaffected by other physical, physiological or psychological factors. Indeed, the entire "Gestalt" school of psychology was built upon the premise that individuals respond to their total stimulus environment. In any case, our experiences in responding to stimuli rarely take the same form as the experimental statement of relationships between physical and psychological quantities.

In addition to all of the considerations discussed above, we must indicate that the literature on visual perception is voluminous and it is beyond the scope of this study to review it all. What has been attempted is a selective review of materials which bear directly on the ability of the astronaut to sense particular types of information which could be used for guidance and control of a spacecraft rendezvous.

Most of the information contained herein comes from studies which were conducted well before the requirements of spaceflight were established. No systematic formulations exist for integrating these data with one another, much less applying them to a complex operational problem. Small differences in method and procedure produce large differences in the applicability of results to applied problems or to one another. Taylor (ref. 8) states:

> "...Since the birth of experimental psychology all aspects of visual experience have been subjected to even more rigorous and quantitative experimentation. As a result the scientific literature abounds in data relating to the visual process. On close inspection, unfortunately it becomes clear that only a very small proportion of these data are useful in formulating productive techniques.
>
> ...Experiments...have been designed to isolate and study single parameters of visual performance...and are, except for rare instances, difficult to apply directly in solving applied visibility problems...Applied experiments...yielded results, which...tend to be directly useful for a specific situation, and which all too often disappear into limbo as soon as the emergent problem has been solved."

Accordingly, the judgment of the individual in using and applying this data are of prime importance.

Related to these considerations is the fact that during the preparation of this document frequent discussion arose concerning an appropriate approach. From one viewpoint it would be most useful if, in the absence of totally objective criteria, the judgment and experience of the authors could be utilized to form usable estimates of the various parameters influencing visual performance. On the other hand, strict scientific rigidity frequently offered no alternative than to discard a particular reported result as not being exactly relevant to the quantification of the variable being studied. Again quoting Taylor (ref. 8):

> "The job of evaluating either the sufficiency or the applicability of some piece of reported research is time consuming admittedly, yet to take it on faith that an adequate study has been performed because the title and abstract so state is sometimes disasterous."

Actually, we judge our produce to be a result of both points of view for we have attempted to at least illustrate the qualitative nature of phenomena, but also by example to indicate the necessity for more exacting study of the particular situations representative of the spaceflight visual environment.

For the reader interested in pursuing further some of the areas of study presented here, the following sources are recommended:

For general reviews of visual perception.

- Vision and Visual Perception; C. H. Graham (Ed).
- Handbook Experimental Psychology; S. S. Stevens (Ed).
- Light, Colour and Vision; Y. LeGrand.
- Handbook of Human Engineering Data; Tufts College.

For analysis of visual problems as applied to spaceflight.

- Vision in Military Aviation; J. W. Wulfeck, et al.
- Bioastronautics Data Book; P. Webb (Ed).
- Visual Capabilities in the Space Environment; C. A. Baker (Ed).

For systematic treatments of visibility.

- Vision Through the Atmosphere; W. E. K. Middleton.

Visibility; S. Q. Duntley, et al.

For general articles on vision in spaceflight.

Seeing a Satellite from a Satellite; I. Schmidt.

For general methods and procedures in behavioral measurement.

Experimental Methods and Instrumentation Psychology; J. B. Sidowski (Ed).

Statistical Principles in Experimental Design; B. J. Winer.

The following sections on visual capabilities discuss the area of visual sensitivity, the sensing of cross range information and the sensing of range information. In the section on visual sensitivity we have tried primarily to outline the factors which determine whether a specific stimulus produces sufficient energy at the receptor to be detected, in a sense analagous to the question of absolute sensitivity and resolution of a sensor with respect to the parameter of energy amplitude, or intensity. Accordingly it underlies the question of whether any useful information can be derived from a stimulus situation for it defines whether or not anything will be seen. In the sections on sensing of cross range motion and range motion, we have attempted to analyze the physical environment situation to determine what cues are available to serve as a basis for sensing the particular type of information required. The major effort is directed towards assessing how well these cues might be used as a basis for sensing information under relevant spaceflight conditions.

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SENSITIVITY OF THE EYE

General Characteristics

The visual system adjusts its sensitivity to a level related to the prevailing luminance, a fact which is apparent to anyone who considers his own experiences in transitioning between areas which are differentially illuminated. One of the most common instances is that of entering a movie theatre on a bright summer day. Initially it is difficult to see detail, and color is totally absent. The bright screen is immediately visible but only gradually is one able to make out the outline and limited detail of aisles, seats, and other persons. Upon re-entering the street there is a period of extreme light adaptation where the individual squints in order to reduce the amount of light entering the eye. Clearly the process of adjustment takes time, and the functional capability of the visual system changes. Any description of visual performance must consider as a primary factor the level of ambient illumination, and any spatial or temporal changes in this illumination to determine the operating point of the eye and establish boundaries which help define the basic visual capabilities under the existing environmental conditions.

Two mechanisms operate to adjust the sensitivity of the visual system; (1) changes in pupil size, which modify the amount of light that can enter the eye, and (2) changes in the sensitivity of the retina which can be considered to adjust the gain of the visual system. These two factors might be looked upon as roughly analagous to an automatic camera diaphragm, and a photographic emulsion whose sensitivity adapts to the level of illumination. One of these two factors, changes in retinal sensitivity, covers a far greater range than does charge due to pupil size. In the following sections we will treat pupillary phenomena and adaptive processes.

In the section on pupillary response the effect of changing luminance conditions are illustrated in terms of lags, duration, and amplitude of pupil response to step function inputs. Long term responses to steady or oscillating stimulus inputs are demonstrated. A relationship is presented which permits the estimate of pupil size as a function of ambient illumination and a discussion of the concept of retinal illuminance, or light energy effective on the retina is presented. These illustrations should provide a basis for understanding and estimating the effective light energy as a function of stimulus conditions and pupillary responses.

The discussion of adaptation illustrates how the sensitivity of the eye varies as a function of the ambient illuminations in the visual environment which might be encountered in spaceflight. Sensitivity is generally studied by exposing the eye to a pre-adapting or pre-exposure field of known luminance, durations and size, and then measuring the sensitivity of the eye to light during a period of time after this pre-exposure field has been extinguished. Thus, the eye is in darkness and, up to a point, the longer it remains in darkness the more sensitive it becomes. As will be discussed, the functional capabilities of the eye change during this process of adaptation.

In a more detailed description of the process of adaptation, the general time course of adaptation is described, considering variation among individuals and within the same individual. Changes in sensitivity which occur when an individual goes from a bright to a dimmer, but not dark visual environment, are discussed, as are the changes in sensitivity which occur from illumination transients. In this category are included single pulses of light, gradually changing levels of illumination, and periods of intermittent illumination. The effects of pre-exposure conditions on the subsequent course of adaptation are illustrated. How the visual task required during adaptation, whether it be the detection of light, the discrimination of one brightness from another, the resolution of acuity targets, or the detection of colored lights modifies the sensitivity curves, is considered.

A final section deals with sensitivity relative to the discrimination of a simple target from its background, where the background is not of zero illuminance. This area, visibility, draws heavily upon the more basic study of what are essentially difference thresholds requiring the discrimination between two different luminance fields. Since sensitivity is modified when a state of relative motion exists between target and observer, and by factors such as size and shape, some consideration is given to how these factors can be treated in assessing the ability of the eye to detect targets.

Pupil Responses

Primarily, in response to changing condition of illumination, the pupil constricts and dilates, varying in diameter from about 3 to 8 millimeters. Accordingly, the amount of light falling on the retina varies as a function of pupil diameter over a range of 16 to 1. This can be compared to the range of adjustment due to retinal adaptation which varies from a minimum detectable level of 10^{-6} ml to an upper level of 10^{5} ml which is intolerable. This is a range of ten million to one.

Retinal illuminance. - Retinal illuminance is expressed in trolands, defined as the amount of light entering the eye from an object having a luminance of 1 candle per square meter and an effective pupillary area of one square millimeter, given as;

$$E_r(\text{trolands}) = 10r_p^2B,$$

where r_p is the radius of the pupil and B is the luminance in millilamberts.

If a systematic relationship exists between field luminance B, and pupil size it would be possible to establish the level of retinal illuminance directly from knowledge of the prevailing field luminance, or as is generally termed, the adapting luminance. Such a relationship has been proposed by DeGroot and Gebhard (ref. 21) based on a review of eight studies (fig. 27) where a large adapting field was employed. They have derived the following expression for pupil diameter as a function of adapting luminance;

$$\log D_o = 0.8558 - 0.000401(\log B + 8.1)^3$$

where D_o is the diameter of the pupil and B is the luminance of the visual field in millilamberts.

The conversion to effective retinal illumination is not a direct one due to the Stiles-Crawford effect (ref. 45). Stiles and Crawford demonstrated that the effect of a ray of light entering the eye decreases as a function of the deviation of its point of entry from the center of the pupil. A small pupil is accordingly more efficient than a large pupil. Using the data of Moon and Spencer (ref. 36), Jacobs (ref. 31) formulated the following equation to describe pupil effectiveness;

$$F_e = \pi D_f r_p^2(1-0.0425r_p^2 + 0.00067r_p^4)$$

where F_e is the net effective flux for any pupil radius, r_p, and D_f is the luminous flux density at the pupil. D_f is constant for a uniformly lighted pupil. DeGroot and Gebhard utilized this relation to formulate an equation for the effective retinal illuminance;

$$E_r(\text{trolands}) = 10r_p^2B(1 - 0.0425r_p^2 + 0.00067r_p^4)$$

where E is the retinal illuminance in trolands and B is the luminance of the adapting field in millilamberts. These equations may be used to determine retinal illuminance for relatively steady state illumination where the pupil size is fairly constant.

Pupillary responses to light. - Figure 28 shows the general form of pupillary response to a short light pulse. With low light levels the latency of the response of the pupil is generally longer than ½ second and the subsequent contraction of the pupil is slow, of small magnitude and short duration. Increasing the stimulus intensity decreases latency and produces a larger, faster, longer lasting contraction. The general shape of the response wave form is the same. Figure 29 shows the extent, duration, and latency of the pupil response to a 1 second flash of indicated intensities. When short flashes of light are presented in rapid succession, the individual pupil reactions summate (fig. 30). Mean diameter decreases with increasing stimulus frequency. When the flash lasts longer than the latent period, changing aperture size will influence effective retinal illuminance since the pupil is closing while the stimulus is still on.

When the eye is exposed to continued stimulation, the pupil contracts, then dilates partially, and begins to oscillate (fig. 31). Equilibrium is reached in about 6 seconds. In dim light, the resulting oscillations are smaller and steadier than in higher intensities where the oscillations reach a maximum of about 2 cps.

The pupil also shows spontaneous contractions and dilations in fatigued observers. Recently a great deal of interest has been generated in pupillary responses as an index of stress or workload (refs. 3, 30). It should be cautioned then that changes in pupil size can come about due to factors unrelated to illumination levels.

An extensive review and analysis of pupillary responses is presented by Lowenfeld (ref. 34) and by Lowenstein and Lowenfeld (ref. 35). Lowenfeld's most important conclusions are paraphrased in the following paragraph. Factors such as level of adaptation, and the intensity, duration, waveform, and frequency of the stimuli all influence pupillary responses.

In the normal, dark adapted eye stimulus intensities below the photopic range can produce small pupillary contractions. The threshold is higher foveally than peripherally, is higher for smaller stimulus fields, and is related to the apparent brightness of stimuli of different wavelengths. In the normal light adapted eye the threshold is much increased over the dark adapted eye and the periphery is no longer more sensitive than the fovea. When suprathreshold stimuli are applied the pupillary response increases in amplitude.

Retinal Sensitivity

While the pupillary system has a time constant on the order of seconds the process of retinal adaptation has a time constant on the order of several minutes in response to steps of the same magnitude. If we go from bright daylight to complete darkness the pupil will respond and stabilize in some 5 seconds while the retinal sensitivity will change for a period of some 45 minutes.

This process reflects, for the most part, a reversible photochemical change in the cells of the retina which increases or decreases their sensitivity to light. The retina is composed of two types of primary receptors, rods and cones, which may be functionally as well as anatomically differentiated. The spatial distribution of the rods and cones over the retina is illustrated in figure 32. Table XIII, after Stiles, et al. (ref. 44), outlines the major functional differences between rods and cones.

Schmidt (ref. 43) describes the boundaries which separate the functionally different levels of sensitivity as follows:

Photopic: cone vision greater than 3 ft. lamberts.

Mesopic :	rod and cone functions overlap	less than 3 ft. lamberts and more than 3×10^{-4} ft. lamberts, varying with the location and size of the retinal area simulated.
Scotopic:	pure rod vision	less than 3×10^{-4} ft. lamberts to absolute threshold of 3×10^{-9} ft. lamberts. Fovea is non-functional in an area approximately 2½ degrees vertical x 3 degrees horizontal.

The eyes have an average sensitivity level determined by those luminances to which they are predominantly exposed (refs. 5, 43). When there is no effective luminance, e.g., darkness, the sensitivity of the eye is discussed in terms of its absolute threshold. When there is some prevailing luminance, the sensitivity of the eye is discussed in terms of a difference threshold, namely, the difference between the prevailing field luminance and that of the object to be discriminated. Depending on the time involved and the nature of the prevailing illumination the eye may be in the process of adapting, or may have reached a steady state.

The following discussion concerns the factors which determine (1) the manner in which visual sensitivity changes; (2) how this change is affected by the conditions which preceded the process of adaptation (pre-exposure); (3) how adaptation is affected by the conditions to which it is adapting; and (4) how the functional capability of the eye varies with changing sensitivity.

The experimental measurement of adaptation. - A brief discussion of the methods and procedures used in the study of dark adaptation will be helpful in understanding the subsequent discussion with respect to how data are obtained. The manner or method of derivation cannot be divorced from the nature or applicability of obtained data.

Studies of adaptation are usually performed by first exposing the observer to a pre-exposure field of a given area, intensity, and temporal characteristics. This field is extinguished and the observer views a fixation point through an artificial pupil. Observing the fixation point maintains the optical geometry so that the stimulus falls on the same portion of the retina each time it is presentd. The artificial pupil serves to eliminate the influence of pupillary adjustment to the ambient light level since it is typically smaller in diameter (2-3mm) than the smallest natural pupil. Another technique for the same purpose is the use of a Maxwellian view. While the observer continues to view the fixation point, brief flashes of light (0.015-0.020 secs) varying in intensity are presented, and the minimum detectible intensity (absolute threshold) is recorded as a function of time from the termination of the pre-exposure period. Increasing the area or the intensity of the test flash can lower the obtained threshold values. Thresholds derived from a number of presentations are typically given as the value of the test stimulus which can be detected 50% of the time. Threshold values yielding the 95-100% detection can be estimated by adding .3 log units to the stated thresholds. Training of the observers is required in order to obtain reliable, consistent threshold data.

<u>The general course of adaptation</u>. - We shall define dark adaptation as the progressive increase in visual sensitivity to light energy which occurs when the observer is in a "totally" dark environment. The envelope for typical dark adaptation curves is shown in figure 33. The initial sensitivity is established by the luminance of the pre-exposure field. The initial portion of the curve drops rapidly before levelling off. This portion of the adaptive process is due to a change in sensitivity of the cones. A second drop occurs rather abruptly at the "cone-rod break". After some 30 to 45 minutes a roughly asymptotic level is reached. In the region of .001 ft. lamberts of prevailing luminance, all portions of the retina are equally sensitive.

In addition to being influenced by stimulus conditions, the general time course of adaptation varies between individuals and within a given individual from time to time. As with all phenomena related to behavior, individuals vary in their visual sensitivity. Variations in a population of 110 normal subjects are shown in figure 33. The shaded area indicates the limits for 80% of the measurements.

In an extended study repeatedly measuring the course of adaptation of three subjects in 24 sessions conducted over the course of 11 months, Mote (ref. 38) reports that a typical "good" adaptation curve lay entirely within +/- .1 log unit of the mean value for a subject. Figure 34 shows the variation in standard deviation from all Mote's sessions as a function of time in the dark.

Mote reviews and summarizes previous findings as follows:

> "The standard deviation for unselected men and women in the general population varies from .25 to .40 log units, becoming perhaps as large as .70 log units. The final level of adaptation usually demonstrates the least variability. Thresholds for individual subjects may vary with a standard deviation of .2 log units on repeated measures."

In an applied sense, the changing level of sensitivity is a problem. Taylor (ref. 48) describes a technique used to reduce the uncertainty involved in the estimation of meteorological visibility where visibility is measured by the apparent brightness of a distant light source. To prevent changes in adaptation and thus in sensitivity the observer is provided with a constant luminance field against which he sees an array of luminous points of controlled intensity. Using this technique, a brightness match of the points with the field results in a range estimate. Taylor uses this example to support the contention that laboratory data can be directly useful once the adaptive state has been specified and maintained.

Apparent brightness of stimuli during dark adaptation. - During the course of adaptation the subjective brightness of a stimulus changes. Van Den Brink (ref. 47) studied this phenomena by requiring observers to adjust a stimulus seen by the light adapted right eye so that it appeared equal to a standard viewed by the dark adapted left eye. The stimulus seen by the right eye eventually appeared dimmer and then increased in apparent brightness as the right eye dark adapted. Consequently the observer reduced the luminance to compensate. These data are presented in figure 35. In a similar procedure the observers adjusted the intensity of the stimulus to the left, dark adapted eye, making it appear equal to a physically constant stimulus in the right eye. These data are shown in figure 36.

Adaptation to intermediate luminance levels. - Rarely will an operational situation be found where the astronaut's eyes will adapt to total darkness. Indeed, it is more probable that the actual periods where constant luminance fields exist will be far too short to permit complete adaptation. Hattwick (ref. 28) has studied the time course of adaptation from a high pre-adapting steady field to various intermediate luminance levels. Figure 37 shows the relationships obtained for foveal and parafoveal stimulation (8 degrees off fovea). In both figures it is clear that the final level of sensitivity is asymtotic as a function of the level of the prevailing luminance. From these data it appears that the course of adaptation to intermediate levels of illumination is roughly similar to that for adaptation to complete darkness.

Baker (ref. 7) has studied the course of light adaptation to intermediate levels of higher intensity than the initially prevailing luminance. Figure 38 shows the threshold retinal illuminance from 5 to 1000 seconds after the onset of various adapting fields. Maximum sensitivity is reached between 100 to 200 seconds after exposure to the new adapting field. This point is preceded by a marked increase in sensitivity and a much more rapid decrease with the passage of time.

Adaptation level and difference thresholds. - The situation which prevails when the subject has attained a steady state of sensitivity, as demonstrated by the assymptotic levels in Hattwick's data which calls for the observer to make a brightness discrimination; to determine the minimum intensity which is detectably different from the prevailing adapting field. If the prevailing field were completely dark it would be proper to consider the same discrimination as a determination of the absolute threshold. Difference thresholds are typically measured by requiring a subject to discriminate between two test fields, where one represents a generally prevailing level of illumination and are obtained after the eye has reached some steady state of adaptation. Thus Hattwick's data represent a transition between two different techniques. Brown and Mueller (ref. 17) thoroughly discuss the considerations relating to method and procedures.

Immediate responses to illumination transients. - There are changes in sensitivity which occur within several seconds of the onset or termination of an abrupt change in luminance. Baker (ref. 7), in a summary paper indicates that the time course of sensitivity is rather complex. The first half second of response is characterized by a marked increase in threshold followed by an extremely rapid decrease. These changes, which seem to be due to neural responses, precede the general course of change in sensitivity. Data from Crawford (ref. 20) shown in figure 39 indicate the nature of this effect relative to a ½ second pulse of light. A sharp elevation of threshold at the onset of the light is followed by a rapid drop. If the pulse duration were extended, e.g., maintained as a continuing illumination level, the course of sensitivity would proceed as described in figure 38 discussed above. At the termination of the pulse, another rapid change in sensitivity occurs.

While not showing the very short term response as dees Crawford, the data from Nutting (fig. 40) shows the threshold luminance for detection of a point source immediately after termination of adapting fields of various intensities. From these data it is possible to determine if a given point source will be detected immediately upon entering the dark after having been adapted to various higher luminance levels.

Figure 41 taken from Van Den Brink (ref. 47) (after Stevens and Stevens) shows subjective brightness in brils as a function of luminance for different adaptation levels immediately after the adapting field was extinguished. A bril is defined as the brightness seen by the dark adapted observer when he views a luminance of 40 db above a threshold value of approximately 10^{-10} lamberts. Clearly the apparent brightness is not a simple function of stimulus intensity.

Boynton and Kandel (ref. 13) present results demonstrating that the sensitivity of the eye is in part determined by neural "masking" effects which occur in response to a stimulus. These neural phenomena mask, or cover up the effects of photochemical phenomena, sometimes completely blocking the transmission of nervous impulses which would normally follow the presentation of a test flash.

Recovery of sensitivity after exposure to illumination transients. - The changes in sensitivity due to transients in illumination may persist beyond the duration of the immediate response described above. These longer term changes involve the photochemical mechanism. If we assume that the eye is adapted to some intermediate luminance we can conceive of many situations where brief flashes or pulse trains of light might be introduced into the visual field. A beacon itself represents one source. The requirement to illuminate briefly a cockpit work area is another. An attitude maneuver, bringing the window from shadow to sunlight is another. In general, these transients will produce a short term decrease in sensitivity. There are a number of investigations in the literature which bear on this problem.

Grant and Mote (ref. 24) deal with the effect of three minute periods of intermittent stimulation introduced during the course of dark adaptation. Table XIV summarizes their findings. The rise in threshold after the flash exposure was found to be a function of both intensity and duration of the flashes. The immediate recovery (after 30 seconds) compensated for all but the brightest, longest flash pattern. The amount of recovery after 30 seconds was significantly affected by the duration but not the brightness of the flashes. After 4 minutes there was recovery to the original level from all but the most disruptive flash pattern (1600 ml/1.0 secs.). From their figure it appears that the most disruptive flash pattern had the effect of producing an assymptotic level of sensitivity some ½ log unit above the maximum sensitivity reached by the control and other experimental groups.

Mote, Grant and Hoffman (ref. 40) performed a study investigating the effects of brief flashes of light (2 seconds) on adaptation in the periphery. As intensity, duration, or both were increased, they found the initial threshold rose, the slope of the adaptation curve decreased, and the time to final threshold increased.

Schmidt (ref. 43) reports the work of Eckel who studied the effects of introducing 5 second flashes of varying intensity on the sensitivity of the dark adapted eye. Recovery from these flashes was relatively rapid with preflash levels of sensitivity being restored in 1 to 3 minutes.

In a study by Kryieleis, also reported by Schmidt (ref. 43), it was demonstrated that blinking the eyes reduced recovery time from intermittent stimulation to 1/3 of that reported when blinking was prevented. Recovery to a log 5 mml level of adaptation after exposure to a five second flash of 496 ft. lamberts took 30 seconds when blinking was prevented.

Recovery to a terminal level took 6 to 7 minutes. When blinking was permitted total recovery took 2 minutes. Flash duration (1 or 5 secs.) did not significantly affect recovery.

Allen and Dallenbach (ref. 1) concluded that the introduction of flashes of 48 ft. candles of 40 msec duration, 1 meter from the eye, produced little variation in the course of adaptation and whatever changes in sensitivity did occur were not measurable after 2 to 4 minutes.

Suchman and Weld (ref. 46) extended the work of Allen and Dallenbach by varying flash duration and intensity. All flashes produced an abrupt rise and a more gradual decline in the threshold. The longer durations had greater disruptive effects. Return to preflash level of adaptation was always complete within 5 minutes and there was no effect on the terminal level of sensitivity. The relative effect on threshold sensitivity decreased as flash duration increased.

In a study by Johannsen, McBride and Wulfeck (ref. 32) on foveal sensitivity, the effect of various combinations of intensity and duration of short light flashes was studied when presented after 10 minutes of adaptation. It was demonstrated that when the combination of intensity and duration was less than 100 ft. lambert-seconds no measurable foveal adaptation occurred. Above this value the effect was found to increase as a function of the product of intensity and time. All combinations of .1, 1.0, 10.00, and 100 ft. lamberts at 1, 10, and 100 seconds were studied. These data demonstrate the rapid recovery of cone sensitivity.

J. L. Brown has performed a series of studies on visual performance related to various aspects of dark adaptation. Of particular relevance is a recent study of the time required for the detection of acuity targets following exposure to brief flashes of light (ref. 14). Specifically Brown studied the effect of adapting flash luminance, target luminance, and angular size of the target (expressed as required visual acuity) on the time to perceive targets. Subjects had been dark adapted for 20 minutes. The primary practical conclusion is drawn from the fact that increasing target luminance markedly decreased perception time. Thus, Brown states, that increasing the luminance of the visual task immediately following a flash will permit rapid recovery of visual performance. However, it is apparent that this will also disrupt the adaptive state. Brown found that spectral characteristics of the disrupting flash had little effect except for very dim targets. Based on data from this study (fig. 42) and experimental and theoretical results in the literature, the following equations were proposed to define the principal relationships influencing recovery of visual sensitivity:

$$t_L = 0.2 + b \frac{(2.7 - \text{Log } L)}{\text{Log } \frac{L}{L_o} \ (2.7\text{-Log } L_o)}$$

where, t_L = perception time in seconds

L = target luminance in ft. lamberts

L_o = minimum luminance at which the display can be perceived

b = slope of a straight line of best fit.

The term b is a function of both the level of adaptation and target characteristics and is related to the flash energy by a power function. For the acuity targets used by Brown the values of b are given as:

$$b_{0.08} = 0.108A^{0.58}$$

$$b_{0.026} = 0.022A^{0.68}$$

where, A represents the adapting flash energy in ft. lambert-seconds, and 0.08 and 0.026 represent the acuity required to resolve the gratings.

For flashes of less than 1 msec., Brown reports the equation yields estimates which are too high. In a later paper (ref. 14), summarizing phenomena related to flash blindness, the foregoing relationships are considered as applicable. In addition, some consideration is given to techniques for ameliorating the effects of flash brightness through the use of goggles, eyeblinks, training, adding illumination and other techniques.

For short exposures, Bartlett (ref. 8) sums up the overall luminance-duration relationships as follows:

> "....for small areas in either the periphery of the fovea complete reciprocity between time and intensity exists up to some duration...and thereafter the threshold will be independent, or nearly so, of flash duration...The facts can be

summarized by generally noting that temporal integration of luminance appears to provide thresholds for human responses up to the neighborhood of 0.08 to 0.11 seconds. Thereafter the critical sensory events have been initiated and integration becomes progressively less complete until, finally, luminance alone determines whether or not a response will occur."

Adaptation after gradual changes in field luminance. - Walsh (ref. 50) discusses the influence of adaptation on making absolute judgments of light intensity. Because the eye has such an extended range of sensitivity (10 million to one) variations of 10 to 1 or as much as 100 to 1 are "... often scarcely noticed if the change is not too sudden". If, for example, a stimulus of constant intensity is presented to the eye during the course of adaptation, this stimulus will appear to grow brighter as the eye grows more sensitive (see fig. 35). If, however, the rate of change of this stimulus is low enough, it may not appear to change, and may in itself cause the eye to adjust sensitivity. Anstis (ref. 4) in a recent publication demonstrates a number of phenomena which result from slow changes in the adapting stimulus. When the adapting luminance is changed over 2 log units in a repetitive sawtooth pattern, and then held steady, the steady light appears to increase or decrease in brightness depending on whether the slope of the sawtooth was positive or negative. These data are suggestive of complicated effects which were not yet fully explored in the reported article.

Mote and Forbes (ref. 39) measured dark adaptation following pre-adaptation to steadily increasing or decreasing luminances. Higher initial thresholds and longer times for the attainment of complete dark adaptation were found when pre-exposure was from zero to maximum luminance rather than the reverse. The two ramp conditions used were roughly equivalent in total energy. With the decreasing luminance condition, there was a tendency for more rapid adaptations following pre-exposure. The most marked differences were found at the beginning of adaptation for exposures greater than 1 minute and 225 ml where differences were on the order of .6 to .8 log units. These differences disappeared after some 10 to 15 minutes.

The effects of pre-exposure. - We have discussed the process of adaptation by assuming that the eye was initially adapted to a photopic pre-exposure luminance field, and have indicated how variation occurs during the course of adaptation. We have also restricted the discussion so far, to the simple problem of detecting a threshold signal, typically white light. Now we shall examine some effects on the process of adaptation due to events that occurred before the process was initiated.

It has been amply demonstrated that the characteristics of the pre-adapting field influence the course of subsequent adaptation. The overall adaptation curve shown in figure 33 occurs when the eye has been exposed to sufficient light energy to drive the photochemical process to the point where both the rods and cones are thoroughly light adapted and are relatively insensitive to light energy. Thus, the typical cone-rod break occurs. When the pre-adapting intensity is low (lower mesopic range) no such break occurs and the course of adaptation is described by a smooth curve dropping rapidly from an initial level. These relationships are demonstrated in figure 43.

Pre-adaptation duration influences the subsequent course of adaptation. Figure 44 demonstrates that increasing the duration of the pre-adapting field up to a duration of four minutes produces more gradual adaptation. At the luminance used however, increasing the duration beyond this time did not further alter the course of adaptation.

Johannsen, McBride and Wulfeck (ref. 32) conclude that, "The effect of increasing the brightness and/or the duration of the pre-exposure light is to increase the initial threshold and to prolong the time for the eye to reach a stable level of maximum sensitivity."

The data in figure 45 from reference 6 provides another means for determining the sensitivity of the eyes immediately after exposure to stimuli which are shorter than 150 seconds duration. Assuming, as do the authors, that the eye reaches a relatively steady state of light adaptation in 150 seconds, shorter exposures should have a less disruptive effect on adaptation and thus less decrease in sensitivity. Accordingly, if exposure duration is known, the corresponding ordinate value from figure 36 is used as a multiplier of the luminance of the exposure field to yield an equivalent steady state of the eye. It would appear reasonable then to use Nutting's data in figure 40 to determine the threshold flash luminance.

A review summarizing the effects of pre-exposure conditions on the subsequent course of adaptation has been performed by Anderson (ref. 2). Anderson's conclusions are supported by experimental evidence in each case. She carefully delineates the criteria for accepting experimental data and suggests a number of phenomena requiring further investigation. Table XV taken from her report summarizes the effect of increasing magnitude of each variable (rows), on various portions of the dark adaptation curve (columns). The numbers in the columns correspond to portions of the dark adaptation curve illustrated in figure 33, and are labelled as indicated in Table XV.

Distribution of light in the pre-adapting field. - Baker, Debons and Morris (ref. 5) have investigated the relationship between the intensity and distribution of light in the pre-adapting field and its subsequent influence on the course of dark adaptation. They suggest, as a result of their experiments, that area and intensity are reciprocally related in terms of their influence on subsequent dark adaptation. As a working value they suggest the average luminance of the effective field may be taken as an index of adaptation level, particularly where variation in retinal image position occurs, e.g., where the eye actively scans a visual field.

Variations due to test stimulus conditions. - Previous discussion has treated the test stimulus as a point, or patch of white light. However, as described in the initial discussion of the characteristics of rod and cone function, there are differences in functional capabilities related to changes in sensitivity.

When the observer is required to resolve detail in the test patch rather than simply report its presence the form of the sensitivity curve varies with the nature of the pattern. Figure 46 shows this phenomenon over time when grid lines subtending various visual angles were used as test stimuli. Larger patterns were resolvable at lower intensities, and the curves are assymptotic as a function of angular size of the test grid elements. Figure 38 shows the resolution thresholds for detail of various angular size immediately after the termination of pre-adapting fields of varying intensities. When a series of visual tasks, carying in complexity, were used to study the course of adaptation, Miles, as reported by Brown, et al. (ref. 16), found that progressively lower thresholds were obtained as the complexity of the task decreased (aircraft orientation, aircraft identification, pattern detection, light detection).

Craik (ref. 19) adapted subjects to a given luminance and then determined visual acuity to a stimulus at various intensities which was presented for 2 seconds. This is roughly equivalent to the method of Nutting for determining absolute thresholds. Craik found that acuity was highest under conditions where adapting and test fields were approximately equal over a range from 10 to 10,000 ft. lamberts. Slightly better acuity was found below 10 ft. lamberts when the adapting level was lower than the test level.

The course of sensitivity during adaptation also varies with the spectral composition of the test stimulus. Chapanis (ref. 18) studied this phenomena for cone and rod vision through a 45 minute adaptation period. His data are presented in figure 48. It can be seen for example that sensitivity to red light never increases beyond the point where the rod cone break occurs. It appears that the rods are more sensitive to the short wavelengths while the cones are sensitive to the long wavelengths.

Monocular and binocular stimulation. - It has been reported that absolute and differential thresholds are modified depending on whether monocular or binocular viewing is utilized. Ronchi (ref. 42) states that the improvement in performance in going from monocular to binocular vision is significant and constant even if of small magnitude. LeGrand (ref. 33) indicates that many researchers report a decrease in absolute thresholds with binocular as compared to monocular regard, but declares that there is controversy with respect to the magnitude of the effect. LeGrand suggests that dividing the monocular threshold value by 1.2 will yield the most reliable estimate of the binocular summation effect. He also points out that the absolute threshold of one eye can be considered as quite independent of the state of adaptation of the other eye, suggesting that a level of sensitivity may be preserved in an alternately bright and dark environment by keeping one eye closed in the light. Bouman (ref. 12) measured thresholds for one eye under conditions where various adaptation stimuli were provided for the other eye. It was found that steady thresholds were not influenced by other eye adaptation conditions. There were momentary fluctuations in threshold when intermittent stimulation was applied to the other eye. This may be a result of neural phenomena as suggested by Boynton (ref. 13).

Differential Sensitivity and Visibility

The considerations discussed above, relative to dark adaptation, apply primarily to the determination of the absolute sensitivity of the eye. We have indicated that the distinction between absolute and differential sensitivity depends upon the method and the purpose of investigation. If the visual field is entirely dark except for the stimulus, and the time course of sensitivity is being measured, emphasis is on adaptation. If the field is not dark, and a relatively steady state of exposure is maintained we typically speak of difference thresholds or contrast thresholds. It is indicated that the study of Hattwick (ref. 28) essentially transitions between these two areas.

The most extensive investigations of differential sensitivity have been conducted by Blackwell and are commonly known as the Tiffany Studies after the foundation which sponsored the research. The most readily available source of these data is the article by Blackwell (ref. 9) describing the studies. Measurement was made of the contrast ratio required for a 50% probability or detection of circular targets (up to 6° visual angle) against luminous fields viewed with binocular vision and with unlimited viewing time. Time and location of stimulus occurrence was known. Figure 49 from the Blackwell studies shows threshold target size as a function of background luminance and contrast ratio. These results have been extended by a number of authors to include larger angular sizes (ref. 48) and to incorporate the effect of different viewing times. Contrast is defined as,

$$C = \frac{B_t - B}{B} \times 100$$

where B_t is the target luminance and B is the background luminance. The ratio varies from zero to 100% for targets darker than their background and from zero to infinity for target lighter than their backgrounds. Although generally used for bright targets on a darker field, the relationship holds for the reverse as well. Several additional studies extending the investigation to non-uniform fields have been performed (ref. 48).

Blackwell (ref. 11) has studied the effects of target size, duration, location, and time of occurrence relative to detection thresholds and discusses the use of weighting factors. Taylor (ref. 49) has studied the effects of practice and claims that a correction factor of 1.90 in contrast ratio will compensate for the difference between naive and trained observers. Blackwell reported a factor of 2.00 in a study cited by Taylor. As a rough rule of thumb to be used where the data were obtained by a yes/no technique, Taylor suggests doubling the liminal contrast value.

From an applied viewpoint, the data for detection of target satellites may be treated as equivalent to the problem of determining thresholds for moving point sources of light, with the additional consideration that the field of view is usually much larger than that employed in studies of motion detection or motion perception. A paper by Gulledge, et al. (ref. 25), treats of the detection of earth orbiting satellites and provides a comparison between contrast thresholds required to perceive static targets and those required to perceive moving targets against the same background luminance. For purposes of their investigation the authors used the fact that a target at different orbital altitude would have different angular rates of motion with respect to a ground observer, and would be moving simultaneously against backgrounds of different intensities as a function of the orbit altitude. Thus their data confound the increase in threshold due to angular rate of motion with the changes due to absolute level of the surround.

Visibility. - Morris (ref. 37) has laid the groundwork for using static contrast thresholds for visibility and applying them to moving targets, by arguing that the duration of the retinal image of the target, derived from the angular velocity, can be used as a basis for comparing these data to the static case. It has been demonstrated (refs. 23, 51) that as the eye searches, it remains stationary, e.g., fixated on a particular point for about 1/3 of a second. Accordingly contrast thresholds obtained with 1/3 second static stimulus exposure durations are used to provide equivalent threshold values to the search case.

Blackwell (ref. 10) states, "Spatial summation of stimulus energy occurs within the visual system, and that an empirical weighting function can be found by experiment which can then be applied to a considerable range of stimulus shapes. Such factors as adaptation, luminance, position in the field, and time of presentation must be considered." Duntley (ref. 22) has developed techniques by which targets with various shapes can be reduced to equivalent discs. Applying these considerations to the Blackwell data, results in a statement of detectability for extended moving targets. Hardy (ref. 27) presents a set of tables for contrast as a function of angular size derived from the Blackwell data, covering the range from .12 minutes to 360 minutes, and background from 10^{-5} to 10^{3} ft.lamberts.

Duntley (ref. 22) presents a review of the extensive work he and his co-workers have done in the area of visibility. We have paraphrased this work for the following statements relative to visual detection of extended objects against sky or planetary backgrounds.

> The description of visual detection task is simplified, because the photometric nature of the object and background can be specified in terms of contrast. Further, the shape of an object is of minor consequence but specification of angular size is quite important. Color contrast has little effect on visibility but influences supra threshold judgment. Duntley states, "....under virtually all circumstances geometrically identical objects are equally detectible if their universal contrasts are equal in magnitude..."
>
> Under conditions of high (daylight) adaptation visual threshold properties are nearly invariant to adapting luminance in the central 1^{o} of foveal area. When objects are small enough to be treated as points they are detectable solely on the basis of flux. At mesopic ranges sensitivity

over the retina is almost uniform but resolution diminishes towards the periphery. At scotopic levels sensitivity is highest in a ring shaped parafoveal area of greatest rod density.

Successive stages of visual performance may be identified as:

detection	- as a spot
recognition	- as a ship
classified	- as a passenger ship
identified	- as a particular ship

Taylor (ref. 48) describes several considerations, termed field factors, which are necessary in converting from laboratory data to field applications. Since these data are statistically derived, and the observer has certain specific information concerning the stimulus such as size, shape, location, duration and time of occurrence. Other factors which are less readily handled include individual differences, training, fatigue, and other secondary physiological and psychological factors. It is pointed out that nearly all laboratory data is collected by the method of constant stimulus and presented in terms of a 50% probability of seeing. It is possible to apply a conversion factor which will yield any desired level of probability. Even this depends on the specific constant stimulus technique employed.

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SENSING MOTION AND CROSS RANGE INFORMATION

Introduction

Information concerning the angular rate of the line of sight is needed for certain visual rendezvous guidance schemes. If one assumes an imaginary line of sight from the eye to the target, then motion of the target projected onto a surface normal to the line of sight can be used to define motion of the line of sight. For a real target moving in cross range at constant velocities, angular rate will change as the object traverses the field. In certain schemes (ref. 5) the rate of motion need not be directly estimated, rather the pilot nulls out any apparent motion of the vehicle across the line of sight. In such cases, assuming a stabilized vehicle, angular deviations from the desired line of sight should be rather small, and consideration of motion in plane or spherical coordinates will yield relatively little difference.

Real motion may be defined as "...the experiential correlate of objective displacement." (ref. 44) There are many examples of apparent motion which are illusions of physical motion when no corresponding physical change occurs. Changes along the line of sight (range) are commonly studied as distance perception, not as motion, and are most often studied as static discriminations, e.g., determination of the range of a single object, or the difference in ranges between two objects. What is commonly studied as motion perception involves the objective displacement of stimuli in a plane perpendicular to the line of sight.

There appears to be very little research which parametrically treats motion along a vector lying out of the frontal or line of sight planes. There are studies which involve the perception of the entire field of view in motion such as those of Gibson (ref. 22). Much of that work is incorporated in the contact analog display system which tries to geometrically recreate dynamic visual aspects of the real world. Pilots are familiar with streaming effects which involve the perception of motion, provide information concerning flight path vectors or ground tracks. Many of the cues subserving these perceptions are unavailable in the rendezvous situation because of the relative emptiness of the visual field.

For our purposes it is necessary to consider that actual spacecraft motions can be resolved into components, namely, range (distance perception), range rate (motion in distance), and cross-range displacement and motion. This is not entirely inappropriate to the relatively impoverished cue environment of space. The guidance schemes amenable to visual implementation can also avoid the necessity for estimating relatively complex relative motion paths. Furthermore, it appears that the sensory basis for making discriminations along the line of sight differs from those used in making discriminations across the line of sight. The cue basis for the perception of motion is not successive stimulation of adjacent retinal areas, for many studies show the stimulus situation to be much more complex, and explanations based on successive stimulation are inadequate. Cues for distance have been extensively studied and are described in detail in another section.

Because we are concerned with deriving guidance information we are primarily interested in the discrimination of motion after a target has been acquired. However, the literature on search and detection, treating of how we find targets, contains much valuable data and there is a certain similarity between the experimental situations in which search, detection and motion are studied.

In the operational situation, it is most probable that the target, when initially detected, will appear as a point or small area source due to the geometry of rendezvous and of flyby missions. There is a substantial amount of data concerning the perception of motion in small targets but relatively little with larger extended sources. Operationally, most targets will be seen against the sky background. In these cases the visible stars can serve as reference points. Some targets will be seen against the background of the earth or moon, or against a combination of field objects, where texture of the object or presence of the horizon might serve as an additional reference.

Phenomenal Characteristics of Motion

The appearance of a moving object changes as a function of its angular rate of motion. Considering centrally fixated objects, several levels may be distinguished (ref. 47). These are:

1. infra-perceptible: actually motion below the absolute threshold for direct perception of motion. Motion is inferred from successive changes in position.
2. perceptible motion:
   a. slow - the object is seen clearly with no blurring;
   b. medium - the object appears comet like, and has a tail;
   c. fast - the object appears all blur, and direction of motion is difficult to discriminate.
3. supra-threshold motion: motion so rapid nothing can be seen.

According to DeSilva (ref. 17), a white vertical bar of light appeared to have the following characteristics as a function of angular velocity:

Velocity (degrees/sec)	Appearance
3-10	distinct moving contours
10-14	slightly blurry contours
14-21	tail appears, form rather vague
21-58	sheet of light, wavering
58-116	slightly vibrating sheet of light
above 116	stationary sheet of light

There is a considerable degree of agreement between these classifications considering the particular stimulus used. J. F. Brown (ref. 6) presents an essentially similar list of changes in the appearance of a moving stimulus as speed is increased and reports similar descriptions in the work of other investigators. It will be seen that these descriptions are also consistent with R. H. Brown's (ref. 10) description of motion. He defines the simplest event as visible motion where the observer must report whether or not a stimulus appeared. This is equivalent to detection and relates to the procedures used in visibility and search calculations. A more complex judgment involves the determination of the direction of motion. An upper threshold is reached when the motion appears as a streak of light and the direction along this streak cannot be discriminated. It should be noted that the relationship between the physical and behavioral phenomena will change as the nature of the observer's task changes from simple detection to more complex judgments.

The exact appearance of the moving stimulus will depend primarily upon its intensity, background illumination, state of adaptation of the eye, rate of motion and exposure duration. A systematic investigation of the factors that underlie the boundaries between the perceptual states might permit a classification of angular rate useful for approximating actual values in operational situations. By describing the phenomenal appearance of the motion the actual rate might be estimated.

Operationally however, it is not always necessary to make absolute judgments of angular rates but only to detect whether or not there is motion. Judgments of absolute rates may be of value in making corrective maneuvers however. Brissenden (ref. 5) emphasizes the importance of establishing the minimum angular rates which can be detected, and gives .1 mrad/sec. as an operational requirement for a line of sight nulling task, where target motion was resolved against a star background. There was no requirement for making an absolute judgment of the actual rate of motion.

Definitions of Thresholds for Motion Perception

In attempting to review and systematize the data on motion thresholds, we have been unable to formulate an entirely satisfactory organization of the types of thresholds because of the variety of methods, techniques, and experimental variables which have been employed. In any case, there are certain distinctions which can be made to assist in understanding just what is measured.

Distinctions between independent and dependent variables. - Independent variables are those physical states or operations established, controlled, and manipulated by the experimenter. They result in changes in some perceptual experience, the measure of which is the dependent variable. More than one independent or dependent variable may be simultaneously introduced into any given experimental situation.

With respect to the study of motion, the primary independent variables can be delineated as follows (ref. 40):

1. physical velocity of the moving stimulus;
2. form and size of the stimulus;
3. presence or absence of fixed reference object and their nature;
4. absolute and relative brightness of the stimulus and the background;
5. absolute and relative color of the stimulus and the background;
6. light or dark adaptation of the eye;
7. monocular and binocular observation;
8. macular or peripheral observation;
9. distance of observation;
10. duration of the observation period;
11. eyes fixated or free;
12. characteristics of the path of movement.

To these we can add the following additional factors culled from our review of the literature:

13. size of the field of view;
14. fatigue;
15. learning effects;
16. method of experimentation.

Particular consideration must be given to the detailed methods of study (item 16) for these differences in experimental procedures yield four threshold definitions as follows:

1. Isochronal thresholds - the duration of exposure is held constant at all test velocities and the extent of travel is varied to produce the constant duration (ref. 35).
2. Isometric thresholds - the extent of travel is fixed and the duration of presentation is varied to produce the constant distance (ref. 35).

3. Heterodimensional thresholds - extent and duration are randomly changed from presentation to presentation. (ref. 35).

4. Displacement thresholds - defined as the smallest angular distance over which motion of a given rate may be judged, produced by varying distance while rate of motion is held constant (ref. 25).

The first three procedures can apply to absolute threshold determinations as well as difference threshold determinations where successive presentations are made of the comparison stimuli. These conditions are described later.

Independent variables and absolute thresholds. - All of the factors listed under independent variables apply to the determination of what has been termed the absolute threshold for visually perceived motion. This is generally determined in situations where a single stimulus is actually displaced with respect to a reference field, which is fixed.

A simple case might involve one point of light which is displaced over time with respect to a fixed reference. Even if only a single visual stimulus is presented, visual motion may be perceived relative to a gravitational frame of reference established by kinesthetic and vestibular cues.

Independent variables and difference thresholds. - Difference thresholds are derived in situations where two stimulus objects undergo actual displacement with respect to the frame of reference. In testing difference thresholds the following additional independent variables are involved:

1. At least two objectively displaced stimuli are presented.

2. Stimuli may be presented close together or separated spatially.

3. Stimuli may be presented successively or simultaneously in time.

Some difficulties arise with these categories for the operations do not produce mutually exclusive effects. For example, two simultaneously presented stimuli may be widely separated in space. They effectively become temporally successive because they are not both within the field of view and require alternate viewing.

Several combinations of two objectively displaced stimulus motions are possible and the resultant thresholds are designated as follows:

1. Differential rate threshold - two stimuli move at different constant rates.

2. Acceleration threshold - one stimulus moves at a constant rate while the second accelerates from this rate to a second rate. Although the technique involves two stimuli it has been termed an absolute threshold (ref. 28).

3. Differential acceleration threshold - two stimuli starting at the same velocity undergo different accelerations.

The stimuli used in these comparisons need not be presented simultaneously but could be presented successively. Some question then arises as to whether there is actually one stimulus or two. For example, it is possible to present a single accelerating stimulus and determine a threshold based on the observer's ability to judge when speed has increased. Another case involves what has been called the instantaneous threshold for velocity (refs. 26, 30, 38). Depending on point of view, this involves the instantaneous change in the velocity of a single target object, or the instantly successive presentation of two different rates of motion.

An example of a threshold measurement procedure which does not fit neatly into the difference threshold category derives from the work of Lina and Assadourian (ref. 34). Here, two vertical lines, presented at various initial separations, were simultaneously moved apart or together. The situation was conceived to be analogous to the change in subtended visual angle of an approaching or receding surface detail. The threshold values obtained for minimum discriminable rate of change were similar to those found when a set of concentric rings was changed in angular size. It appears that the two line situation may be analogous to the displacement threshold involving a change in relative separation as a function of velocity. The exact instructions given the subjects are not stated but it appears subjects were instructed to judge the direction of travel. Data are plotted as a function of response time at each rate, and separation angle.

Response dependent thresholds. - The nature of the obtained threshold may be a function of the response which is required of the observer. Strictly speaking, establishing judgment criteria through the use of instructions is an independent variable manipulation. Instructions are frequently treated as independent variables. Practically speaking, however, we find it more useful to consider the result of these instructions separately from the class of independent variables. The following distinctions between thresholds can be made based on the judgment required of an individual.

1. Detection threshold: The detection of the presence of a moving stimulus in an otherwise static field without the experience of motion per se. This is analogous to R. H. Brown's visibility threshold (ref. 10) and simply requires the observer to report whether or not a stimulus was present during the test interval.

2. Absolute motion threshold: The recognition of the presence of a single moving object in an otherwise static field generally accompanied by the direct experience of motion. Brown (ref. 10) has adopted the criteria that the observer is able to correctly detect the direction in which the stimulus is moving. This is the lowest detectable angular motion.

As is apparent from the preceding discussion, there are a large number of factors which appear to influence the absolute thresholds for motion. J. F. Brown (ref. 6) makes the point that the absolute threshold is dependent upon the conditions of measurement, contending that the definition of a threshold simply in terms of angular velocity is inadequate. He found, for example, that increasing the viewing distance and thereby decreasing the angular velocity of the image on the retina did not correspondingly alter the threshold when all other conditions were identical.

Spigel (ref. 44) states the absolute limen has been shown to be markedly effected by the "stimulus matrix" - "The more homogeneous the field the greater the rate of motion required for the emergence of perceived motion. Lower thresholds were also obtained with decreased size and brightness of the moving target."

Gibson (ref. 23) reports the following summary of facts concerning motion:

1. A pair of visual velocities can be discriminated just as accurately with fixation of the eyes as with pursuit.

2. With motion within a frame, thresholds are lower near the edge of the frame than near the center. "In short, the just noticeable linear velocity varies widely with conditions. No fixed values for an absolute threshold can be obtained."

3. When comparison is made between two widely separated fields, requiring alternate viewing the basis of velocity judgment may be a frequency variable, e.g., the number of "spots" passing by an edge.

4. Differential threshold in a two window situation (where the two stimuli are widely separated) is 10%. When the stimuli are adjacent or superimposed the difference threshold is much lower. There is also a different experience in perceiving velocity under these conditions.

5. Rotating surfaces yield the same discriminations as translating surfaces.

Duncker's work, as reported by Gibson (ref. 23), indicates the presence of a "ground" is extremely important. With only two points, only one of which actually moving, either may appear to move. If a textured field is present then the just noticeable displacement is "extremely small" in the order of seconds of arc.

The section on velocity perception in the Tufts Human Engineering Handbook (ref. 40) presents the following summary statements about the perception of motion:

Path of motion -

Horizontal thresholds are lower

Viewing distance -

Lower angular thresholds are found at longer viewing distances

Exposure duration -

Longer exposure durations yield lower thresholds

Stimulus size -

Increased size decreases apparent velocity, and knowledge of stimulus motion characteristics influences judgment.

Size of field of view -

Increasing field size decreases the threshold. Apparent speeds are greater in small fields .

Illumination -

Threshold values decrease logarithmically as illumination increases linearly.

Retinal area -

Threshold variation among individuals greatly increased in the peripheral retina and marked changes in sensitivity depending on illumination level.

Monocular or binocular viewing -

At closer viewing distances monocular acuity thresholds are increased with motion but no decrease is shown for binocular perception.

Absolute Thresholds for Real Motion

Considering the factors discussed above, there appears to be a fair degree of consistency between the various value of absolute thresholds.

Table XVII is a summary of absolute thresholds determined by various experimenters along with an indication of key experimental conditions under which these values were obtained. Clearly, threshold values are lowered as exposure time is increased, references are provided, or stimulus intensity is increased. For example, the general form of this relationship relating exposure time to threshold as can be seen from the Leibowitz data, is quite consistent with that determined by Brissenden (ref. 5), in a starfield simulation experiment.

Variability in threshold measurements. - R. H. Brown (ref. 12) has compiled data from five studies which demonstrate a relationship between the angular rate of the stimulus and the variability of individual judgments. For a range of .2 to 2000 minutes per second he finds that the variability in threshold measures increases linearly as the mean threshold speed increases. The relationship is expressed as $\sigma = .0859\ M^{.945}$, where M is the mean threshold value. In a later paper (ref. 12) Brown compares laboratory data with field test data obtained on the visual estimation of aircraft speed. The same relationship between mean and variance was found.

Relationship between objective and subjective velocities. - Eckman and Dahlback (ref. 20) performed a study in order to construct a subjective scale of velocity. The procedure known as fractionation was to require observers to adjust a variable stimulus so it appeared to move half as fast as a standard. From these operations over the range of physical velocities from .69 to 5.72 degrees/sec. of visual angle, they derive the equation

$$V_S = 0.1340 \ V^{1.7703}$$

to relate subjective velocity (V_S) to physical velocity (V).

Differences between types of absolute thresholds. - Brown (ref. 10) presents data for what he terms the visibility threshold and the motion threshold (figure 50) where visibility is equated with the simple detection of a light, and motion requires the correct discrimination of direction.

Where simple detection is considered, Brown's data and that of Pollock apply. When the requirement for discrimination of direction is added, it appears that increasing brightness does not increase the threshold.

The data reported by Conklin, Baldwin, and Brown (ref. 16) are obtained in a situation where the subject was required to correctly guess the direction of motion, rather than simply report the detection of a light. Pollock (ref. 39) makes a distinction between detection and recognition which is a still more complex task, and may be considered as equivalent to the problem of dynamic visual acuity.

The upper speed threshold. - The upper speed threshold is that value where the target direction cannot be discriminated and the perception is of a single uniform line of light. Data for this threshold (fig. 51), taken from Brown (ref. 10), indicate this upper threshold is approximately constant regardless of luminance.

Effect of target luminance. - R. H. Brown (ref. 9), using his own data and that of Pollock (ref. 39), demonstrates that rate discrimination thresholds for various combinations of exposure duration and luminance are in accord with the Bunson-Roscoe law for durations less than .1 seconds in that intensity x time = constant. Accordingly the discrimination of velocity is taken to involve a single sensory event determined by the magnitude of the initial photochemical response. This effect is demonstrated in fig. 52. At slow speeds where transient energy level on small areas of the retina are high due to the passing stimulus, threshold luminance is constant but at speeds higher than .5 degrees per second threshold luminance increases until it varies in direct proportion to speed.

In the investigation of isochronal threshold velocities Leibowitz (ref. 31) shows that threshold decreases with increased luminance and increased duration. These data were plotted in fig. 53 with target luminance as the parameter, and in fig. 54 with exposure duration as the parameter.

Pollock (ref. 39) studied speeds from 50 to 2000 degrees per second for a 1 degree test patch, 9 degrees peripheral, obtaining slightly higher thresholds at all speeds for horizontal as compared to vertical motions. The following equations describe the speed-luminance detection threshold relationship:

Overall	$\text{Log } y^1 = .896 \text{ Log } x + .564$
Horizontal	$\text{Log } y^1 = .904 \text{ Log } x + .577$
Vertical	$\text{Log } y^1 = .878 \text{ Log } x + .575$

In the applied setting where subjects searched for a moving target Summers, Shea and Ziedman (ref. 45) investigated the effect of target intensity on detection time and showed that this variable had an effect on initial trials but as the subjects became more practiced the influence of target intensity markedly diminished. In a later study (ref. 42) they performed one study which showed no significant effect due to target intensity, and a second which demonstrated that the effect of intensity was confined to a group of subjects unfamiliar with the particular star pattern against which they were attempting to detect motion.

Effect of exposure duration. - As has been previously stated, increasing the exposure duration decreases the threshold value for motion perception. Examples of this may be derived from Tables XVI and XVII Brissenden (ref. 5), in the applied setting clearly demonstrates the relationship (fig. 55) and the data of Leibowitz (ref. 31) shown in fig. 54 are generally in accord. Thus, the longer the exposure duration the lower the threshold.

Extent of travel. - Again relating the empirical data to the Bunsen-Roscoe Law, Brown (ref. 12) shows, as in fig. 56, that increasing the extent of travel for a stimulus passing over the retina increases the critical duration. The figure demonstrates a constant energy requirement to achieve threshold up to a critical duration whereupon the energy requirement increases as angular speed increases.

Summary of energy relationships. - When the extent of motion is limited, luminance must increase as speed increases in order for the visibility criteria to be met, up to a limiting value of high speeds. At moderate luminance and exposures shorter than the critical duration upper speed threshold increases directly with luminance up to a value which represents maximum speed for motion discrimination where increased luminance no longer increases the maximum detectable angular speed. This value as reported by Brown (ref. 10) is on the order of 36 degrees/sec.

Effect of reference points. - Leibowitz (ref. 32) studied the effect of reference lines on the absolute threshold for angular motion. He found that grid lines had no effect on motion perception for short exposure durations (less than .125 seconds) suggesting that velocity discrimination is determined by the underlying photochemical process of the retina. In other words, the energy impinging on a given retinal area per unit of time is the determinant of a response. At long exposure durations (16 seconds) where judgments of successive position appeared to be involved, reference lines substantially lowered the absolute motion threshold. These data are presented in fig. 57. It is also clear that increased exposure duration or increased luminance lowers the overall threshold.

From studies done against starfield background, it may be seen (refs. 5, 42, 45) that in general increased star density, by providing more reference points and reducing the separations of target and reference, results in improved performance.

Several more applied studies have specifically considered the effect of reference points in the form of the number of star references in the field of view. Brissenden (ref. 5) considered absolute threshold discriminations when the initial separation of the target and nearest star varied from 12.5 to 60 mrad. Detection time increased with increasing initial separation. Woodhull and Bauerschmidt, as cited by Shea and Summers (ref. 42), investigated as one variable the number of background stars in the field of view. With fewer stars it is reported there was difficulty in establishing direction of motion. Both these studies required the report of direction of motion. Summers, Shea and Ziedman (ref. 45) performed two studies where they investigated the effect of practice on the motion detection threshold for moving point sources. They report that memory for the starfield had a significant effect on detection. Shea and Summers (ref. 42) investigated, as one variable, starfield density, and demonstrated the same relationship as before. In a second study, they compared detection performance in situations where the observer had a great deal of experience with a particular starfield and demonstrated that whereas for the unpracticed subject detection time was markedly influenced by target intensity and angular rate, the learning of the starfield reference pattern produced detection performance which was independent of those factors.

The effect of blinking lights on motion thresholds. - If a slowly moving stimulus is made to blink, it will be more readily detected. Studies of "conspicuity" (ref. 21) demonstrate that detection time is decreased when a flashing rather than a steady signal is presented. Baird, et al. (ref. 2) provide data on the use of a grating reticle device which caused a steady illuminated target to appear as a blinking target moving across the reticle. For a line of sight angular rate of .1 mrad.sec. they found gratings which produced blink rates of 6.25 and 10 blinks per minute reduced detection time from 169 to 42 and 35 seconds respectively for a +3.0 magnitude target.

Wienke (ref. 49) performed a detection study in which two flash rates were used with the same motion track. Flashes occurred either once per second or once each ten seconds with interflash displacements of 1° and 10° respectively. The more rapid flash rate yielded better detection performance.

It is reasonable to conclude that these detections involve a displacement threshold rather than the direct perception of motion and the effect of flashing is similar to what would be obtained with static targets.

Motion and absolute sensitivity. - Morris (ref. 37) addresses the problem of determining detection range when the entire field of view moves across the retina. The literature reviewed is that pertaining to motion perception. It was concluded that an effective stimulus duration must be assigned to the target, and Morris takes this as the time required for an image of the target object to move over a point on the retina. Knowing the effective stimulus duration, it is possible to utilize the data of Blackwell by assigning equivalent stationary exposure time, then the required angular subtense can be specified for any given value of contrast and light level. To quote, "...a target moving with respect to the line of sight can be equated to targets flashed on the center of the field for a single brief exposure, equal in duration to the time required for a target to move across a point on the retina."

In this report Morris includes a fairly comprehensive review of the existing literature prior to 1957. The relationship she describes provides a means for equating the visibility threshold, as Brown defines it and the work on threshold contrast.

Difference Thresholds

R. H. Brown (ref. 14) performed a comprehensive review of work relating to the difference threshold for velocity. He distinguishes three different stimulus situations under which velocity discrimination was studied. These are (1) the stimuli are spatially separated but are temporally coincident. They must be viewed alternately; (2) the stimuli are temporally coincident and close together spatially so that they may be viewed simultaneously; (3) the stimuli are superimposed spatially and temporally separate as would be the case with a single target accelerating. Brown thoroughly reviews a series of experiments and provides tables describing the experimental conditions in detail. Table XXI is his summary of the experiments reviewed. For separate stimuli he derives the following equation for the differential threshold:

$$\log \Delta\omega = 1.114 + \mathrm{Log}\ \omega$$

For superimposed stimuli he presents the equation:

$$\text{Log}\,\Delta\omega = -2.893 + \log\omega$$

These data are plotted in figs. 58 and 59.

In a later paper (ref. 15) Brown concludes that the best estimate available of the Weber ratio for velocity discrimination when no more specific information is available is:

$$\Delta\omega = (0.10)\,\omega$$

Lina and Assodourian (ref. 34) performed a study to determine a threshold value for rate of descent as applied to lunar landing. They used two stimulus situations, one in which two lines moved apart from one another, and a second in which a series of concentric circles increased in angular size. They chose as their threshold value the angular rate which could be detected in .2 seconds. The obtained values were predictably higher than a field test from a helicoptor, based on the great differences in the richness of the perceptual field.

In an investigation of the effect of experimental procedure on velocity discrimination threshold, Mandrioto, Mintz and Notterman (ref. 35) studied the effect of spatial and temporal cues. Either of these could be systematically related to the velocity. If a fairly standard procedure is used, e.g., the standard and comparison stimuli move in a field of equal and fixed spatial dimensions, the relative velocities may be inferred from relative duration. In Brown's summary of nine studies, eight were isometric in the sense above. In the other case initially superimposed stimuli moving at different rates produce a subsequent change in position. $\Delta\omega/\omega$ for this latter case were .00128 while in the former they were .1074. These investigators used successive comparisons and a judgment of faster or slower. Their conditions were:

1. Isometric: standard and comparison traversed equal extents, thus transit time varied inversely with speed.

2. Isochronal: standard and comparison were exposed for .06 seconds. Distance traveled varied directly with velocity.

3. Heterodimensional: extent and duration were randomly changed from trial to final.

Their resul. demonstrate that heterodimensional, isometric and isochronal presentations gave successively and consistently lower difference thresholds over the velocities tested from 20.06 to 512.71 min. of visual angle/speed. Above 80.25 min/sec $\Delta\omega/\omega$ was relatively constant. Values estimated from their figures for two subjects are given in Table XXI.

Some additional representative values for various experimental conditions can be obtained from the paper by Brandalise and Gottsdanker (ref. 4), who sued spatially separate but coincident stimuli, namely, two rotating discs separated by a partition. They used the method of average error, whereby the observer is free to adjust the speed of one disc until it appears just different from that of the standard. Perceptually this is a different operation from that of judging whether two fixed values differ. the values obtained by these investigators are given in Table XXII, together with data they present from other studies.

If two stimuli are temporally coincident and in close proximity it may be possible to judge differences in their velocity by changes in apparent relative position. Monocular motion parallax effects are also present. This is considered a cue to depth, and results from the fact that objects at different ranges have different apparent angular velocities. Based on this velocity difference it is possible to judge distance. The threshold for this discrimination is in the order of 30 seconds per second.

Perception of higher order differences. - If the velocity of a target is changing, either with respect to a fixed reference or another object moving at constant velocity we may properly consider that the observer may be able to judge differences in higher order components of motion.

One such situation has been studied by Hick (ref. 30) and by Notterman and Page (ref. 38). They employed a very simple situation in which a single spot traversing the fact of a CRT was instantaneously accelerated to a new velocity. Thus the stimulus was as if spatially coincident but temporally separated were presented. Data from these studies is presented in fig. 56 .

Hick suggests a rough approximation to his data, stating that a difference of about 12% of initial velocity yielded the 50% velocity discrimination threshold, roughly in accord with Brown's best estimates of 100% for other types of stimulus presentation. Notterman and Page take exception to the generality of this statement, and it does appear that at low rates some deviation from this value occurs.

In a review of the detection of accelerated motion Gottsdanker (1956) observes that smoothly accelerated motion is responded to as if velocity were constant. It appears that a fair amount of continued slow acceleration can occur without the observer realizing that speed is not constant. The operator's perceptual mechanism appears to integrate smoothly changing velocities over a considerable period of time. Actually there has been very little work in this area. Gottsdanker reports the statement of Hick and Bates to the effect that their preliminary investigations revealed rate must be doubled every 5 seconds for acceleration to be noticed. Definitions of absolute and difference thresholds for acceleration are presented and discussed by Gottsdanker.

Gottsdanker, et al. (ref. 28), obtained acceleration thresholds by comparing accelerated targets with those traveling at constant rates. They suggest that accelerated motion is identified by comparison of early and late velocities rather than by direct sensing of acceleration. It was found that gradual changes in velocity are more difficult to discriminate than are differences between two fixed rates. As a basis for this, he uses his minimum obtained threshold value of 20% as compared to Hick's data for steps of 9 to 15% and Gottsdanker's figure of 5% given above. At a given velocity, thresholds increased as presentation time decreased and for a given duration thresholds increased as velocity increased. In terms of relative change in velocity, e.g., 100 ($V/\bar{V}$) where V equals the change in velocity during the presentation time, and $\bar{V}$ equals the mean velocity during the interval, the following values are reported for the 75% threshold.

	Exposure Time			
Mean $\bar{V}$	3.64	1.82	0.92	0.45
.96	102			
1.92	54			
3.85		86		
7.69			86	
				157

It is suggested that an overall representative figure of about 90% be taken as an acceleration threshold value. In a later paper (ref. 27), Gottsdanker further analyzes and substantiates these earlier findings.

Dynamic Visual Acuity

Dynamic visual acuity concerns the ability of the visual system to resolve images when a state of relative motion exists between the eye and the target. In such a situation the eye, through the operation of the extrinsic eye muscles which cause the eyeball to move in its socket, performs a tracking function in attempting to follow an object so as to acquire and maintain an image centered on the fovea with minimal error. Within limits anything the eye can follow and keep focused on the fovea will be legible if sufficient time is allowed and if the object would be visible in the static state.

In following a target the eye exhibits a latency of response on the order of 150-200 msec. With rates up to 25 to 30 degrees per second after initial responses and velocity following, saccadic eye motions keep the eye approximately matched in position to about 1° of the target it is following. With rates higher than about 30 degrees per second lags occur, and frequent large saccadic motions are required to null the developed position error. At higher speeds relative angular motions increase and acuity is impaired. Eye movement velocity, however, remains relatively constant with these abrupt saccadic motions superimposed to effect error correction. The eye can follow sine waves up to about 3 cps with amplitudes up to some 30 degrees without appreciable error. In the process of target following, there are then several steps, namely (1) perception of movement, (2) constant velocity eye motions, (3) correction of position error by sacaddic motions, and (4) modification of rate of following in discrete steps. In free field tracking the eyes and head both move. There is typically an initial lag followed by a general leading of the head with superimposed fine corrections from the eyes.

The most comprehensive report on dynamic visual acuity, from which the following paragraph is derived, is that of Miller and Ludvigh (ref. 36). Fig. 48 demonstrates the relationship between angular velocity of the test object and visual acuity for three groups of subjects who differed in their level of performance. It may be seen that performance begins to deteriorate above 30 to 40 degrees per second. Fig. 58 compares data from two experiments, one (Miller and Ludvigh) used constant exposure time by decreasing the field of view as velocity was changed, and the other (Rose) used a fixed angle, thus decreasing the exposure time as speed increased. It is suggested by Miller and Ludvigh that Rose's data are more generally applicable to the applied situation where the angle over which observation is possible is relatively independent of target velocity. In fig. 59 it is demonstrated that motion in the horizontal axis reduces acuity more than does motion in the vertical axis. Similar results are found whether the object or the observer are moving. In line with previous discussion on target luminance and motion detection, it is reported that increasing illumination materially befitted acuity. Individual differences in dynamic acuity are marked, but there is no necessary relation between an individual's static and dynamic acuity. The effect of training differs markedly among individuals; some benefit while others do not, but training in general seems most profitable with higher velocity targets.

Some of the limiting acuity values presented by Miller and Ludvigh appear to result from the procedure which used a restricted pre-exposure time, e.g., the period during which the subject fixated at the position where the target is likely to appear. With limited pre-exposure acquisition is poorer. Elkin (ref. 19) demonstrated that increasing pre-exposure time improved performance. Without limitation on viewing time it appears from Elkin's data that acuity on the order of one minute of arc is obtainable at rates up to about 60 degrees per second. Thus if the eye can acquire, get on target and follow, reasonably good performance can be expected.

Also related to the effects of preceding events on the perception of moving objects is an interesting study by Smith and Gulick (ref. 43) on what they term dynamic contour perception. They demonstrated that the edges of small moving target objects which cannot normally be resolved can be made visible at the same velocity by briefly presenting the same target in a stationary position before it is moved. Interestingly the stationary and moving targets can be presented to separate eyes and resolution will still be facilitated up to about 40 degrees per second when no further improvement is possible. A statistical summation theory is presented to account for these findings.

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RANGE AND RANGE RATE DETERMINATIONS

Introduction

The present section deals with range and range rate determinations. The assumption is made that the primary goal, in the present setting, is to determine: (1) the extent to which visual perception can provide measurements or indexes of range, range differences and range rate, and (2) to place in evidence visual data that might be useful in developing new techniques for obtaining such information visually, alone or in conjunction with optical aids.

In appraising the performance of the visual system in this area, we regard it as analogous to a physical instrument, and ask how well it can do the job of getting information about the range or range rate of objects in the observer's environment. The psychological literature has not been guided primarily by this point of view. One therefore finds a large body of literature in the field of depth perception that is of limited relevance for this question. Most of the investigations have been concerned with the role of particular cues in mediating perceptions of distance. In examining the literature, this basis for classification can scarcely be avoided and is therefore used here. In the following list of cues, the first three are variables that are regarded as capable of operating even with monocular viewing of the visual field; the last two are dependent upon binocular viewing. The cues considered in this section are: (a) accommodation, (b) size, (c) motion parallax, (d) convergence, and (e) binocular parallax or stereopsis. Dees (ref. 16) has constructed a useful table providing an appraisal of the extent to which the various alleged cues to depth perception are likely to be involved in space operations (Table XXIII). Earlier, McKinney, Adams and Arnault (ref. 54) made a similar appraisal with substantially the same conclusions. Dees' table also provides a definition of the various cues of interest.

Perception of Absolute Range

The perception of absolute range refers to an observer's judgment or awareness of the distance, in range, from him to a particular object in the field of vision. The presence of other objects in the field does not automatically eliminate the possibility of perception of the absolute distance to a particular object. We find, however, that investigators frequently restrict themselves to a single object in the field at one time. In this way, they reduce the probability that judgments of relative distance may constitute the real basis for what might seem to be judgments of absolute distance. The investigations of perceptions of absolute distance reviewed below are conveniently classified in two groups: (1) those which attempt to measure the constant and variable errors occurring in judgments of absolute depth, and (2) those which attempt to determine whether certain specific cues to depth play a significant role in the perception of absolute depth.

Errors in judgments of absolute depth. - In the appraisal of any instrument as a range-finder, specification of the constant and variable errors involved would seem essential. This requirement applies to the visual system when used for this purpose as well as to purely physical instruments.

The results of available studies for measuring constant and variable errors in distance-estimates are assembled in Table XIV and a specification of the conditions involved in Table XXV. The index of variable error used is the standard deviation, which is commonly accepted as the best measure of dispersion, due to chance errors, in a group of measurements (ref. 62). The index of constant errors used is the mean judged distance minus the true distance. Errors of under-estimation will therefore have a negative sign; errors of over-estimation a positive sign. Since the investigators cited do not all report in these terms, some recalculation of the results reported by them was necessary to provide a common basis. Thus, when dispersion of estimated distances was reported in terms of the average deviation, multiplication of the average deviation by 1.2532 permitted us to convert to standard deviations (ref. 62, p.81). In the case of other investigators, such as Dees, who reports his results in the form of log-log plots, or equivalent equations, somewhat more elaborate recalculation procedures were necessary. In our table, constant and variable errors are given both as a percentage of the true distance, and in feet. The studies explicitely undertaken to determine errors in distance estimates all involved relatively large distances, up to at least 800 feet and up to a maximum of 4000 feet. This deliberate inclusion of large distances was probably a consequence of the fact that this group of investigators was all oriented toward space-operation problems. Although these distances are large compared to those commonly used in experiments on depth-perception, they are small in relation to distances that may be of interest in rendezvous, as indicated by Table I, given in an earlier section.

Inspection of the tables reveals the following points of interest:

1. In the studies of McKinney, et al. (ref. 54), and Pennington and Beasley (ref. 60), both of which involved control of the same depth-cue (size), there was a fair degree of agreement in the magnitude of the various errors (using the "approach" column of the Pennington-Beasley study).

2. In the case of the constant errors, however, we find that the directionsof the constant errors reported by these two groups of investigators are opposite, underestimation in one case as opposed to overestimation in the other. This conflict obviously requires resolution.

3. When now we examine the magnitude of the errors derived from Dees' study (ref. 16), with stereopsis and parallax as the cues, instead of visual angle, we find only constant errors of overestimation, as in the Pennington-Beasley study (ref. 60). The magnitude of the variable errors for stereopsis are approximately equivalent to those of the Pennington-Beasley approach case, but the parallax errors are appreciably smaller. It would be hazardous, however, to draw the conclusion that the relative magnitude of these errors are a function of the particular cues involved, since Dees' methodology was so completely different from that of his predecessors. Some of the more striking features of Dees' method are the following:

a. The operational procedure of the subjects in estimating distance consisted in estimating the rank order of a given perceived distance, following a preliminary period of training. Dees regards this procedure of estimating ranks as merely a way of coding the various physical distances. The reported ranks were subsequently converted by Dees into alleged equivalent estimates of the distance in feet, thus permitting him to calculate means and errors in feet. The validity of the data cited in our table rests on the validity of this procedure.

b. The stimuli for generating parallax corresponded to oscillations of the eyes of the observer, of one foot, or a total eye excursion of 2 feet. This displacement is obviously much greater than the interocular distance of 2.5 inches involved in the tests of depth perception mediated by stereopsis. We are therefore not justified, on the basis of the relative magnitude of the errors obtained from Dees' stereopsis and parallax data, in concluding that parallax is, under normal conditions, so much more effective than stereopsis as a cue to depth.

c. It is difficult to assess the correctness of the stimuli used by Dees in simulating various cues to distance, since the actual stimulus properties are not specified. We are told only that the film transparencies used for projecting the stimulus patterns were made by means of a "photographic animation stand equipped with Vernac scales which allowed the positioning of the target platform to .0001 in....." This device was used to produce patterns that were equivalent to what the eyes would see at various physical distances. Since good intentions are no guarantees of performance on the part of an experimenter, such specification of stimulus-conditions, in terms of how the stimuli were made, is scarcely an adequate basis for appraisal or replication.

<u>Studies on the role of specific cues as factors in the perception of absolute depth</u>. - A second group of studies has been concerned with the question of whether a particular stimulus variable is adequate to serve as a cue to absolute depth. Two types of cue have been explicitly investigated in recent studies: (a) stimulus size, and (b) convergence.

a. <u>Size as a cue to absolute depth</u>. A concise survey of the literature on this question up to about 1960 has been given by Ittelson (ref. 45, p.70). The list of the earlier workers includes Bourdon (ref. 10), Peter (ref 61), and Bappert (ref. 6), in studies concerned primarily with accommodation, and Pouillard (ref. 64), Peterman (ref. 63), Vernon (ref. 78), and Hirsch, et al. (ref. 38), in studies more specifically concerned with the role of the size-cue. Ittelson (ref. 45) believes that the most decisive evidence has been provided as a consequence of the proposal of Ames of a method, for localizing in depth, a monocularly viewed object in relation to a binocularly viewed comparison field. This method was developed further by Hastorf (ref. 34), in his study of the effect of suggested meanings on the relationship between stimulus-size and perceived distance, and by Ittelson (ref. 46) in his investigation of size as a cue to the static perception of distance. To this list of Ittelson's must be added papers by C. and J. Hochberg, in 1952 (refs. 39, 40), and one by Gogel, Hartman and Harker in 1957. In examining the literature concerned with the size-cue it may be helpful to note the large number of different terms that may be used to characterize different distance or size-variables. A display of such terminology is given in Table XXIX. It may also be helpful to keep in mind the geometrical relations involved in the operation of the "size-cue" to depth-perception. These relations are reviewed in the introduction to a later section, concerned with the role of size in perceptions of relative depth. Figure 64 indicates that the term size might refer to object-size, to physiological or retinal size, the magnitude of the image on the retina, or to the angle subtended by an object, at the eye, designated as the visual angle. The discussion of the geometry of the situation shows the relation of these three meanings of size.

Ittelson (ref. 46) and Gogel and co-workers (ref. 29) reach opposite conclusions concerning the effectiveness of stimulus-size in mediating perceptions of absolute distance. Ittelson concludes from his experimental evidence that the size of the retinal image, operating in conjunction with an "assumed size" of the stimulus-object, can bring about the perception of a single object, viewed monocularly, at a definite distance, in depth (ref. 46, p. 66), a distance predictable from certain hypotheses. Gogel and his coworkers concluded, on the basis of a different method of investigation, that analysis of his data "revealed no evidence for the presence of absolute distance-perception as a function of retinal size." In discussing Ittelson's experiments, which had been carried out some years earlier, he expresses the belief that in none of Ittelson's studies "has the possibility been eliminated that the perception which was measured was a perception of relative, not absolute, distance." (ref. 29, p. 2) Thus the question at issue is whether or not what seem to be perceptions of absolute distance, in a given investigation, might actually depend on perceptions of relative distance. Hochberg and Hochberg (refs. 39, 40), in discussing experiments of their own, on the perception of the distance of familiar objects, raises similar questions. They question, too, the necessity of the concept of the "assumed size" of familiar objects, originally proposed by Ames and utilized by Ittelson in explaining and predicting the apparent distance of objects at which physical objects subtending a given visual angle will be perceived.

On the basis of the literature to date, it seems necessary to conclude that the adequacy of the size-cue in mediating perceptions of absolute distance is still a controversial matter. There seems to be substantial evidence and arguments on both sides of this controversy. Further analysis and experimentation are therefore indicated.

b. Convergence of the two eyes as a cue to the perception of absolute distance. In a later section, the possible role of convergence in mediating perceptions of relative distance is considered, and should be examined for matters of history. Gogel (ref. 28) investigated convergence specifically in relation to perceptions of absolute distance. His method involved the use of two alleys, as in the recent experiments on the role of retinal image-size. One alley was viewed monocularly and the other binocularly. Analysis of the data led Gogel to the conclusion that there was a small but significant effect of convergence on perceived distance, but that it was "an unprecise and usually negligible determiner of perceived size and distance". The maximum distance involved in his experiment was 34 feet.

Perception of Relative Range

This section includes perceptions in which an individual observes and reports on range intervals between two or more objects, as when one object is perceived and reported as nearer or farther away than another. Such observations can be made even when judgments or estimates cannot be made of the absolute distance of either object from the observer. The great bulk of the literature on the perception of depth lies in this field.

Accommodation as a cue to the perception of distance. - The mechanism of accommodation, the means by which the eye focusses images sharply on the retina, as the distance of the object changes, was the subject of controversy for over 200 years. Boring (ref. 9) cites six theories of accommodation proposed during this interval, each theory with its complement of supporters. The theory now generally accepted, that the lens changes shape, thus altering its focal length, was proposed by Descartes in 1637, but it was not generally accepted until Helmholtz, in 1856, marshalled the evidence in favor of it. Helmholtz also proposed an explanation of how the ciliary muscle controls the shape of the lens, contractions of the ciliary muscle resulting in increased curvature of the lens, and therefore a reduced focal length.

The problem of salient interest here is not, however, the mechanism of accommodation as such, but its role in mediating perceptions of relative distance. The fundamental lines of inquiry were established in the early days of experimental psychology. Wundt, in 1859-1861 (ref. 84), conducted experiments with threads viewed against a white background. The thread could be displaced in distance relative to the background in successive presentations. The subject was asked to report whether the thread had approached or receded in successive views. Threshold determinations were made. These showed smaller values for binocular viewing (convergence presumably operative) than for monocular viewing (involving, it was assumed, accommodation alone). In the latter case, thresholds were smaller for approaching objects than receding ones. This effect led Wundt to conclude that a subject can make more accurate discriminations by "innervating" the muscle of accommodation than by relaxing it. The maximum absolute distance involved in these experiments was 2 meters.

Hillebrand (ref. 37), about 30 years later, in 1894, criticized certain features in Wundt's technique and conducted experiments on his own. In place of threads, he used the sharply cut edge of a cardboard screen viewed relative to a more distant background. Hillebrand thus proposed to avoid changes in visual angle associated with a thread at different distances. When the screen was made to change in distance gradually, instead of suddenly, the subjects were unable to tell in which direction it had moved. Hillebrand concluded, in opposition to Wundt, that perceptions of distance cannot be brought about by cues from accommodation. About 10 years later, Baird (ref. 4), in this country, reviewed the literature and conducted experiments of his own in an attempt to resolve the controversy. He used Hillebrand's type of target, the edge of an areal extent, and tried to determine thresholds for both monocular and binocular viewing, for both approaching and receding visual targets. He was able, unlike Hillebrand, to establish threshold values, reporting them in the form of a Weber fraction, as a percentage of the absolute distance involved. His results were in substantial agreement with Wundt's findings. Binocular thresholds were appreciably less than monocular thresholds, and monocular thresholds consistently less for approaching objects than for receding ones. He concluded that accommodation did provide a cue to the perception of distance. It should be noted, however, that the maximum absolute distance that could be used in Baird's apparatus was slightly less than one meter. The term "Weber-fraction", as used here, refers to the ratio of the difference threshold to the total physical distance from the observer's eye to the target. It may also be stated as a percentage value, by multiplying the fractional ratio by 100.

Subsequent experiments in this area were carried out by Peter, in 1915 (ref. 61), by Bappert, in 1922 (ref. 6), by Fincham, in 1951 (ref. 22), and by Campbell and Westheimer, in 1959 (ref. 13). The latter two groups of investigators found a basis for discrimination of the direction of out-of-focus blurring of images on the retina. They found that a subject could distinguish blurring in an image focussed in front of the retina from one focussed behind, thus providing a cue to the change in shape required of the lens. Thus we see that the evidence relative to accommodation as a cue to distance perception continues to oscillate back and forth, even to the present time. Perhaps the best that can be done by way of a decisive summary-statement is that of Graham: "...discrimination of depth differences based on accommodation are neither precise nor accurate over distances greater than a meter or two." (ref. 30, p. 52.) It is of interest that Descartes, three centuries earlier had stated in L'homme, 1662, p. 54, that accommodation is effective up to 3 or 4 feet and convergence up to distances of 15 or 20 feet (ref. 18, p. 305). Reviews, in addition to that of Graham, that may be consulted are those of Hoffman (ref. 41), Woodworth (ref. 81), Irvine and Ludvigh (ref. 43), and Ogle (ref. 57, p. 265).

Size as a cue to distance. - In the present section we are interested in the role of size as a cue to the perception of relative distance. Size will be taken to mean visual angle (that is, the angle subtended at the eye by the object), for reasons to be given below. It is the impression of many psychologists that there is a large volume of literature available on this problem. There is indeed a large volume of literature in the general area of the size-distance relationship. But the bulk of this literature is concerned with the phenomenon of size-constancy, and other problems relating to factors in the perception of size of objects, rather than on the role of size in the perception of distance. Our present inquiry is directed specifically to our ability to obtain information about distance. Reports on the perception of size are therefore not directly relevant.

The term "size-constancy", a concept apparently introduced by the Gestalt school of psychology, refers to the tendency for receding objects to be perceived, or judged, to be of constant size despite the progressively decreasing visual angle. This effect is most marked when there are plentiful cues to the increasing distance (ref. 45).

a. Geometry of the size-distance relationship. Fig. 64 shows the essential geometrical relations involved. Straight lines, or rays, through the end points of an object AB are represented as passing through the nodal point N of a reduced schematic eye (ref. 78) to the terminal points of an image A'B' regarded as focussed on the retina. If the lens is regarded as approximated by a thin lens, then the rays through the nodal point will not be refracted. In this simplified diagram,

$$\tan \Theta_s = \frac{\ell}{D} \qquad (1)$$

For small angles,

$$\Theta_s = \frac{\ell}{D} \text{ in radians} \qquad (2)$$

The object, of length ℓ, is spoken of as subtending a visual angle Θ_s at the eye. It is apparent from the equations above that the size of the subtended angle will depend on both object-size, ℓ, and object-distance, D. The geometrical information a single eye receives is limited to the size of the image on the retina. This image size can in turn be regarded as providing an index of the subtended angle Θ_s, since the length of the eyeball, and therefore the image-distance in the eye is constant.

Since the visual angle is a function of both object-size and distance, it is impossible for any optical system such as that of Fig. 64 to provide information about the object-distance specifically, unless there is some basis for eliminating the object-size, ℓ, as a variable of the equation. Two ways of accomplishing this may have relevance for depth-perception: (a) If the size of the object, ℓ, is known, then it can, in effect, be inserted in Eq. (2) and the distance, D, be calculated from the subtended angle, Θ_s.

(b) If, in a given situation, the size of the object, although unknown, can be assumed to be constant, then any variations occurring in the subtended angle can be attributed to distance variations alone. Thus, in Eq. (2), the total distance will be inversely proportional to the subtended angle. This relationship provides a conceivable basis for the physiological control of perceptions of relative distance. What is being suggested here is that the observer, in his perceptions, may behave as if he were utilizing Eq. (2) as a basis for perceiving relative distances in depth from the direct sensing of differences in size between images and therefore between subtended visual angles.

What justification is there for assuming that Eq. (2), representing a purely geometrical relationship, can be regarded as a relationship used by the individual in converting the sensed size of retinal images into perceptions of absolute and relative distance?

Ittelson designates this assumption, that apparent size and apparent distance can be substituted for size and distance, respectively, in Eq. (2), the size-distance invariance hypothesis. He then uses this modified equation as a basis for predicting the "apparent distance" to be expected in various experimental conditions (ref. 45). Woodworth and Schlossberg (ref. 82), in their well known text, used a similar procedure in attempting to provide an understanding of experimental results in this area. Ittelson reviews the evidence in some detail. It is quite easy, however, for any individual to demonstrate to himself the plausibility of the equation. First note that perceived size varies concomitantly with visual angle in two objects of different size viewed from the same physical distance; then note that perceived distance varies inversely with visual angle, by viewing two objects of the same size at different physical distances. The combination of these two relations in the same equation gives one the equivalent of Eq. (2), but with apparent size and apparent distance taking the place of physical size and physical distance as variables, respectively.

Two innovations are utilized by Ames, as reported and subsequently further investigated by Ittelson (ref. 46) in the use of this equation in the perceptual field: (a) the utilization of a psycho-physical method of equivalents for getting quantitative measurements of apparent or perceived distance, which can then be substituted in the equation, and (b) the proposal of the concept of "assumed size". The concept of assumed size for familiar objects permits one to get numbers to substitute for the size variable in the apparent-size and distance form of Eq. (2), or to regard a constant, representing assumed size, to be substituted for apparent size, thus providing an algebraic equivalent for the observed inverse relation between visual angle and perceived distances. The above discussion of the geometry of the size distance relationship is, of course, relevant to perceptions of absolute distance and to perceptions of movement mediated by differences or change in visual angle, as well as to perceptions of relative distance.

b. Experimental studies. On the adequacy of size as a cue to relative distance, we find quite general agreement. It is in the realm of perceptions of absolute distance that the major differences appear. The demonstration in pictures, dating from the time of Leonardo de Vinci, that the larger of two drawings of the same object is interpreted as closer, is the prototype for findings in this area. Overt experimental studies have been carried out by: Ames (ref. 1, 41), Bourdon (ref. 10), Peter (ref. 61), Bappert (ref. 6), Pouillard (ref. 64), Peterman (ref. 63), Carr (ref. 14), Ittelson (ref. 47, 48), and Hochberg (ref. 39, 40).

In general, it is found, as one is led to expect from the geometry of the situation, that perceived distances are inversely proportional to the subtended visual angles. When the angles change continuously in time, at a rapid enough rate, this relationship can account for the perception of continuous movement in range, as considered in the sections dealing with this topic. The investigations of Ames and his associates have probably provided the most important recent work supporting the role of size as a cue to distance (refs. 1, 34, 46, 47). This emphasis on the importance of the size cue was possibly a consequence of Ames' observations of the effects of aneisekonia, unequal retinal images in the two eyes, in his clinical work with patients.

Motion Parallax

A concise characterization of the term "motion parallax" and its relation to depth perception has been given by Graham, et al. (ref. 30, p. 205).

"When an observer views monocularly a visual field containing objects at different distances, movements of the observer's eyes with respect to the visual field or movements of the visual field with respect to the observer's eyes cause a differential angular velocity to exist between a line of sight to a fixated object in the field and a line of sight to some other object. The condition of differential angular velocity holds for binocular vision as well as monocular. Objects farther away than the fixated object appear to move more slowly than the fixated object and, if the observer is moving, the farther objects appear to move in the same direction as the observer. Objects nearer than the fixated object appear to move faster than the fixated object and in the opposite direction. The greater the distance between objects the greater the difference in apparent speed. This phenomenon is called monocular movement parallax and provides an important cue for monocular space perception."

Thus parallax implies the subtending of an angle at the eye by two points lying at different distances from the observer, and motion parallax refers to the change in this angle as the eye moves relative to the two points.

Contributions bearing on the role of motion parallax in depth perception have been made by the workers listed in Table XXX. This table indicates the chronology of the various reports and the chief problems considered by each investigator. In the following sections, the status of contributions to these problems will be summarized.

Geometry of Motion Parallax

Parallax due to eye displacement. - Ogle has presented a diagram to represent the geometry of parallax when two points in space, P and F, are assumed to remain fixed and the eye moves along a line at right angles to a line through the two points. The essential features of Ogle's diagram are shown in Fig. 65. Ogle's diagram has been altered in a few non-essential details to facilitate the derivation of equations and comparison with other diagrams (ref. 16, pp. 263-264).

From this diagram, Ogle derives two equations. Eq. (3) shows that the ratio of the parallax angle ρ to the angle ϕ through which the eye has rotated, while shifting through an extent s, is equal to the ratio of the depth interval $(y - y_o)$ to the total distance y. Eq. (4) shows that this same ratio of depth interval to total distance is also equal to the ratio of the angular velocity of parallax angle ρ to the angular velocity of the eye-rotation angle ϕ. It must be noted that in the analysis the angles ρ and ϕ were assumed small and thus; $\rho \approx \sin \rho$, $\phi \approx \sin \phi$ and $y^2 >> s^2$.

$$\frac{\rho}{\phi} = \frac{y - y_o}{y} \tag{3}$$

$$\frac{d\rho}{dt} \Big/ \frac{d\phi}{dt} = \frac{y - y_o}{y} \tag{4}$$

Parallax due to moving points, with eye fixed. - The diagram of Graham, et al., to represent this situation, corresponding to conditions operative in their experiments, is shown in Fig. 66. We have emphasized certain lines in the diagram, to better bring out its equivalence to Ogle's diagram. Comparison of the two indicates that Fig. 65 can be used to represent either situation, that in which parallax is brought about by the shift in eye position, or that in which it is brought about by simultaneous movement of the environmental points as a group, in a direction perpendicular to the original line of regard. In the former case, that of the laterally moving eye, points P and F are fixed, and the eye moves from point A to point B, while continually fixating on F. In the latter case, the eye is regarded as located at B, and object-points P_1 and F_1 move through an extent s, along parallel lines at right angles to the initial line of regard BP_1, terminating in final positions P and F respectively. Table XXVIII shows, in the first two columns, the equivalence between the symbols used by Ogle and by Graham, et al. Graham and his co-workers derive Eq. (5) and Eq. (6) as a basis for the computations they subsequently perform with their experimental data (ref. 32, p. 208).

$$\frac{d(\Delta\Theta)}{dt} = -\frac{\delta}{R_f} \cdot \frac{d\Theta}{dt} \tag{5}$$

$$\omega_t = \frac{\Delta\Theta}{t} = - \frac{\delta\ t}{R_f} \cdot \frac{\Theta}{t} \qquad (6)$$

The definitions of terms can be found in Table XXVIII, the equations of Graham, et al. (ref. 32), and Ogle (ref. 16, p.262) for representing the relations involved in parallax look quite different. It may however merely be a matter of different symbols and arrangement of terms. If we substitute Ogle's symbols for those of Graham in the latter's Eq. (6), we obtain an equation almost identical with that of Ogle's Eq. (3). The difference consists only of a y_o in place of y, in the denominator. In addition, a difference in sign may occur if one is not careful to make the positive directions of the equivalent angles correspond. The difference in the denominator term is not critical, since δ , the difference between y and y_o, is stated by Graham to be very small compared to either of these two terms. Hence it is immaterial whether y or y_o is used in the denominator. In a similar way, Graham's Eq. (5) can be translated into Ogle's Eq. (4). The two pairs of equations are thus equivalent, and it is in the interests of simplicity to use just one set of symbols for both situations. We therefore propose to use those of Ogle.

Threshold determinations. - Parallax thresholds have been reported by Tschermak-Seysenegg (ref. 76) and by Graham, Baker, et al. (ref. 32). The determination of these magnitudes were in a sense incidental to the special problems of the investigators, so that it is necessary to scrutinize their papers to find appropriate data. The authors do not themselves indicate that they are attempting to establish normative or representative values for parallax thresholds.

Two types of threshold seem to us to be of interest as indexes of a subject's ability to use parallax as a cue to depth: (1) the ratio $\frac{\rho}{\phi}$ as defined by Ogle (parallactic angular ratio) (ref. 16, p. 263); and (2) the differential angular velocity ω_t as defined by Graham, et al. (ref. 32, p. 208). Both of these variables are considered in the section on the geometry of parallax. Threshold values are collected in Tables XXIX and XXX. It should be noted that the parallactic angular ratio is not given explicitly by either Graham, et al., or by Tschermak. The values entered in Table XXIX have been calculated from sections in their reports in which measures of parallax thresholds $(y - y_o)$ are given in linear units, in association with a specification of object distance. Then the ratio $(y - y_o)/y$ can be calculated, as indicated in Eq. (3), to specify ρ/ϕ. In relating ρ/ϕ to the thresholds for other cues to depth perception, it should be noted that this ratio is formally equivalent to a Weber fraction. Since it is equal to $(y - y_o)/y$, it places in evidence the fractional part of an object-distance y that can be detected by an observer by means of parallactic angular movements.

It is of interest that the absolute distances involved in the experiments cited were extremely small, relative to absolute distances likely to be involved in space operations. It was between 9 and 10 inches in the experiments of Graham, et al., and approximately 8 inches and 16 inches in experiments of Tschermak. If one should wish to apply these threshold determinations to an estimation of the depth interval or rates that can be detected at large absolute distances in space, then an inquiry into the validity of such extrapolation is in order. These experimental determinations of parallax thresholds are the best that are available, indeed the only ones available. If they are of possible practical significance in the space-operations, then there is need for equivalent investigations at large absolute distances. Dees' investigation of the role of parallax in depth perception was carried out at relatively large physical distances. But the results were not formulated in the form of the parallax thresholds that we have been discussing, and it is not immediately apparent whether they can be translated into such terms.

Effect of certain parameters on parallax thresholds. - Parameters regarded as possible factors in influencing parallax thresholds have been assembled in Table XXXI, with associated columns to show the source of these data, and results obtained.

In some instances in which a particular parameter has been investigated by more than one worker, we find agreement in the effects observed; in others we find disagreement. Graham, et al. (ref. 32), and Zegers (ref. 85), for example, are in agreement that thresholds are increased with increased rate of relative movement of the stimulus-objects and the eye. Rose (ref. 66) and Graham, et al. (ref. 32), on the other hand, differ on the effect of a change in axis of motion parallax from the horizontal to the vertical axis. Graham, et al., report an increase in threshold; Rose, a decrease. Table XXXI is intended to indicate only the general direction of change of parallax thresholds with increase in the specified variable. More specific data on changes in values for some parameters are shown in Tables XXIX and XXX. Curves showing the form of the functions involved for some of these parameters when used as variables may be found in the paper of Graham, et al. (ref. 32).

Phenomenological experiences of depth. - Gibson, et al. (ref. 26), have criticized the tendency of previous investigators to speak of motion parallax as a cue to depth in the absence of direct evidence that subjects have the actual experience of perceiving depth when reporting detection of parallax-angles. They therefore set themselves the task of determining whether subjects spontaneously reported on experiences of depth when conditions were set up to generate geometrical parallax. Two types of situation were considered: (a) the empty field situation, in which parallax was produced by discrete points or objects, as in the experiments of Graham, et al., and (b) the continuous field situation, in which there was a gradient of motions from a continuous surface relative to some reference point. The latter situation is one that may be not uncommon in an earth-bound situation, but it is probably extremely rare in rendezvous operations in space. In general, Gibson, et al., frequently failed to obtain spontaneous reports of experiences in depth even when geometrical motion parallax was present. Such reports became more frequent when the subjects were given appropriate supplementary information about the situations they were to observe.

Convergence as a Cue to the Perception of Depth

Convergence refers to the fact, illustrated in Fig. 67, that when an observer fixates a point on an object in front of him, the two eyes will rotate so that their lines of regard will intersect at the point fixated. This fact, according to Boring (ref. 9, p. 271), was known to the ancients, for example, to Euclid, but its possible significance for depth perception was not realized until much later. At this later period, the key names were Aguilonius (1613), Descartes (1637), and Berkeley (1709).

Aguilonius, the inventor of the concept of the horopter thought of it as a plane containing the point of fixation, so that the distance of this plane from the observer would depend on the angle between the two eyes. Horopter is a term used to designate the locus of all points in outer space which an observer will see as single when both of his eyes are fixated on a particular point, P. Descartes (ref. 9, p. 271) somewhat later, described the eyes as feeling out the distance to an object by the convergence of the optic axes, and apparently believed that the individual could sense the angle between the eyes as a means for apprehending the distance of the object. Berkeley (ref. 9, p. 272), not accepting Descartes' view of a direct sensing of the angle of convergence, speculated on how the idea of the distance to an object could be derived from the sensations he assumed were produced by the movements of the eyes in convergence. He developed an associationistic type of theory, based on previous experience of the individual, that was not different in essentials from the views held by Helmholtz, by Wundt, and by Titchener, about 2 centuries later (ref. 9, p. 272).

Graham (ref. 30, p. 520) points out that experimental investigations of the role of convergence in depth perception fall into two classes: (a) determination of depth thresholds for convergence (through binocular viewing), generally in conjunction with the determination of such thresholds for accommodation (through monocular viewing), and (b) experiments utilizing stereoscopes in which it is possible to change convergence without appreciably altering accommodation. Investigations falling in the first class were carried out by Wundt (ref. 84), Hillebrand (ref. 37), Arrer (ref. 3), Baird (ref. 4), and Peter (ref. 61); in the second class by Swenson (ref. 72), a student of Carr (ref. 14), by Grant (ref. 33), and by Gogel (ref. 28). Graham, after reviewing these studies, concludes that "convergence provides, at best, a minor system of cues to distance" (ref. 30, p. 521). Ogle (ref. 16, p. 266) comes to a similar conclusion. This statement, reflecting no doubt the status of research in this field, is not altogether satisfactory from the point of view of definiteness and unambiguity. To achieve anything better, further experimentation, based on critical and probably laborious analyses of previous investigations would probably be necessary.

It is conceivable too that the questions asked concerning the role of accommodation and convergence in the perception of depth need reformulation. Even though unequivocal evidence that these mechanisms provide effective cues to the perception of distance may be wanting, it is possible that their importance lies in their role of an underlying and indispensable mechanism. Thus convergence may be necessary in order for the optimal degree of retinal disparity to be provided as a cue for stereopsis rather than as an immediate source of cues to distance. Considering convergence from this altered point of view may lead to different and more fruitful questions to be asked of experiments than have generally been considered in the past.

Stereopsis

Stereopsis refers to the perception of depth produced by a disparity, or lack of correspondence, of images in the two eyes resulting from the different positions of the eyes when viewing a three dimensional object or scene. If the disparity between the images is too great, double visual images occur; if the disparity is too small, the perception of depth will not occur. Hence one of the principal problems is that of specifying these limits in quantitative terms. In the present section, after an introductory account of geometrical relations involved in the measurement of stereopsis, we shall summarize the principal experimental findings with respect to the stereoptic threshold levels found and the parameters influencing them. A final paragraph will consider mathematical functions experimentally established, under conditions of binocular viewing, which show equivalent depth intervals as a function of absolute distance.

<u>Geometrical relations</u>. - Fig. 67 is a simple diagram designed to show the meaning of the stereoscopic angle η. The fixation point F and another point P, lying behind F, are represented as lying on the optical axis of the left eye (L. E.). The right eye (R. E.) is also fixated on point F. The depth-interval FP thus subtends an angle η, at the nodal point of the right eye. This angle represents the angular disparity between the retinal images of point P on the left and right retinas (ref. 16, p. 292).

One of the chief techniques used for measuring the effectiveness of stereopsis in mediating depth-perception has been that of determining the angular disparity threshold, the minimum value of η required in various situations for the depth-interval FP to be detected. The usual statistical conventions should, of course, be utilized in the determination of this threshold, as with any other.

It will be of interest to compare this diagram with that of Fig. 56, used to represent the geometrical relations in monocular parallax. It is apparent from inspection that the two diagrams are geometrically identical. It requires only a change in interpretation for the same diagram to be used for both cases.

On the basis of the diagram in Fig. 67, Ogle derives the following equation (ref. 16, p. 292), which shows how the depth interval Δb_v depends on the viewing distance b_v, the angular disparity η, and the interocular distance $2a_o$. By assuming a representative value of 6.4 cm. for the interocular distance, and some specified value for the threshold angle η_t, based on experimental determinations, he is able to calculate functions showing how the minimum detectable depth interval Δb_v will vary as a function of the viewing distance b_v. Computations of this sort may be of value in connection with rendezvous space operations in indicating the minimum depth intervals required at various viewing distances to be detectable by means of stereopsis.

$$\Delta b = \frac{b_v^2 \eta_t}{2a_o - b_v \eta_t} \tag{7}$$

A table of Ogle's showing the results of such calculations for various assumed values of η_t is reproduced as Table XXXV (ref. 16, p. 293).

Through the use of Eq. (7), one can also determine the maximum viewing distance, b_L, at which it is possible to detect any depth interval, however large, by stereopsis. In Eq. (7), we may ask what conditions will make the detectable depth interval Δb_v infinite. This condition will come about when the denominator expression equals zero. Thus, if $(2a_o - b_v\eta)$ is set equal to zero, then

$$b_L = \frac{2a_o}{\eta_t} \tag{8}$$

This equation indicates that the maximum viewing distance for stereopsis depends only on the interocular interval $2a_o$ and the threshold angle η_t. This distance can be increased only by increasing the interocular interval or decreasing the stereoptic angular threshold. Such conclusions indicate the need of either appropriate selection procedures, for personnel, or the use of appropriate optical aids.

Experimental determinations. - The absolute levels of stereopsis threshold is shown in Table XXXIII. The effect on the threshold level of various parameters is shown in Tables XXXIV and XXXV for stimulus parameters and receptor parameters, respectively. It should be noted that the reciprocal of the threshold disparity angle is referred to as stereoscopic acuity, a procedure corresponding to that used in specifications of visual acuity (ref. 16, p. 286).

Mathematical functions representing stereoscopic depth perception. - Although not belonging exclusively in this section, it is of interest to consider certain attempts to represent the manner in which the capability for relative depth perception, presumably mediated by stereopsis plus supplementary monocular cues, changes as a function of physical distance of the perceived object from the subject. Gilinsky (ref. 27) derived such a function on the basis of perceived increments in depth that were greater than threshold, and Teichner a function based on threshold increments (ref. 75).

Gilinsky asked her subject to use as a reference standard what they thought was the extent marked off by one meter (in another experiment, one foot). Then, starting from the position of the subject, she laid off markers, under instructions from the subject, to correspond to successive subjective increments of one meter. The length of these successive increments was measured in physical units. If now the psychological units, extents perceived by the subject as all equivalent to one meter, are regarded as all equal, we may lay off the successive physical increments on the x-axis, to correspond to the successive increments of equal sense-distances on the y-axis. We thus obtain a curve of perceived distance as a function of physical distance. Gilinsky's equation for representing this function is:

$$\frac{d}{D} = \frac{A}{A + D} \qquad (9)$$

where d_p is perceived distance,

D is true distance, and

A is maximum limit in perceived distance for a given observer.

Ogle, in discussing Gilinsky's data, proposed a somewhat modified equation shown here as Eq. (10) (ref. 16, p. 256).

$$d_p = K_1 \log (D + d_o) \qquad (10)$$

where d_p is the perceived distance,

D is the objective distance,

d_o is a space correction factor for an error in the origin of the data, and

K_1 is a constant, found to equal 7.92 for Gilinsky's data.

An investigation by Teichner, et al. (ref. 75), upon depth discrimination under commonplace viewing conditions also led to an equation showing the way depth discrimination changes as a function of distance. The apparatus used was modeled after the Howard-Dohlman apparatus frequently used for determination of thresholds in depth (ref. 86, p. 454). Instead of rods, however, these workers used two large black rectangles, 66 inches by 72 inches in size. One rectangle was fixed at each of a series of distances extending up to 1500 feet, and the other varied in position until it was judged to be at the same distance as the other rectangle. The method used was thus a form of the psycho-physical method of equivalents. The standard deviation of difference in distance between the two rectangles (from the observer) was used as an index of precision. This quantity can also be used as a measure of the difference threshold, since it can be regarded as lying at the border line between depth-extents seen as equal, and those seen as not equal, on a statistical basis. When Teichner, et al., plotted the standard deviation as a function of the observation distance, they obtained a curve slightly concave upwards. By the method of least squares they found the following equation to give a curve of best fit.

$$S.D. = 0.002 D^{1.35} \qquad (11)$$

where, S.D. is the standard deviation, in feet, and

D is the true distance, in feet.

The authors point out that the accepted equation for the precision of stereoscopic depth is:

$$S.D. = K\ D^2 \qquad (12)$$

The difference in the exponents in these two power functions indicates that the difference threshold, under the conditions of Teichner, et. al., increases more slowly with distance than would be true if the determining factor were stereopsis. They conclude that monocular cues to depth perception were also involved. Finally, they conclude from reports of their observers on the method they used for detecting differences in distance that vernier acuity probably provided the chief cue to depth-discrimination, as used in this study. Vernier acuity refers to the ability of an observer to detect a break in a long line, when one part of the line is displaced relative to the other. It is possible to specify an angular threshold, corresponding to the visual angle subtended by the distance of displacement. Berry, et al., have reported such vernier acuity thresholds to be quite small, of the order of 2 sec. of arc (ref. 8). In Teichner's experiment, subjects reported that the edges of the two test-target squares were seen as lying on the same straight line when the targets were seen as the same distance away, and that they (the subjects) used the displacement of the edge of one square relative to the other as an indication of a difference in depth. Although the conclusion of the authors that vernier acuity probably formed the basis for judgments of relative depth in this experiment seems justified, it does not necessarily follow that the equation derived by them to represent depth discrimination as a function of distance will hold, if conditions are arranged so that subjects cannot rely on this accidental juxtoposition of the two rectangles for making their judgments. The function derived in this experiment may possibly be an artifact of the technique used.

Range Rate

Operations of pilots in rendezvous maneuvers are obviously dependent on information they are able to obtain concerning the properties of motion of pursued vehicles relative to their own. Another section of this report deals with cross-range motions. The present section will review the situation with respect to the perceptions of movements in range. As a point of departure, we again take the point of view that the visual system can be considered analogous to a physical instrument, and ask about its capabilities for obtaining information about range motions of external objects. If we were designing an instrument for this purpose, we would want to determine the instantaneous velocity as a function of time during any specified time interval. By integration and differentiation, we could then also determine distance traveled and acceleration, respectively. A search for literature in this area indicates that the questions that have been asked are much more modest, a function in part of the extremely limited number of investigations directed explicitly to the problem of the perception of motion in range.

Perçeption of real movements in range. - We have found only two investigators concerned with range-movements who have utilized real movements in range in their experiments: Ittelson, in 1951 (ref. 47), and Baker and Steedman, in 1961 (ref. 5). Baker and Steedman were apparently unaware of Ittelson's investigation, since they make no reference to it. They regarded their experiments as an extension of the experiments of Smith (ref. 67, 68, 69), who worked wholly with simulated perceptions of movement. Their utilization of real movements was a consequence of the particular technique they developed to set up perceptions of movement based on size changes. They were apparently not concerned about any distinction between real and simulated movements. Ittelson utilized real movements in range in order to permit his subjects to compare the monocularly observed perceptions of simulated movements produced by continuous size changes with the perceptions of real movements.

The essential features of the apparatus used by Ittelson for producing both real and simulated movement in the same visual field are of interest. His experiments on movement used the same basic apparatus that was used in his experiments on static perception in depth.

> "...a two alley set-up, one alley containing the experimental field in which the stimulus situation being studied can be placed, and the other alley containing the comparison-field relative to which apparent distance can measured. A

system of mirrors enables O to see both alleys simultaneously and apparently directly in front of him.

"The stimulus-situation used consisted of two parts. the first was a cart bearing a light-box with a square aperture 3¼ in. x 3¼ in. illuminated from behind, Target A. This cart was motor driven on tracks in such a way that the target moved back and forth, between two points 6 and 12 feet in a radial direction from O, at a constant speed of 36 ft. per min., requiring 10 sec. to cover the 6 ft. of travel.

"The second part consisted of a light-box at a fixed distance of 9 ft. from O, containing a similar illuminated aperture of variable size, Target B. The size of this target was controlled by the motion of the cart carrying Target A, so that the size-change of B was always synchronized with the motion of A. Target B varied from a 2½ in. to a 4 3/4 in. square, subtending the same range of visual angles as Target A." (ref. 47)

Ittelson states that the reports of his subjects indicated that radial movement of target B was perceived, as a result of the continuous size changes, that was indistinguishable from the real radial movement of target A, a result which supports his conclusion that retinal size must be considered an adequate cue to the perception of distance.

Baker and Steedman (ref. 5, 70) took as their problem the determination of thresholds by the method of constant stimuli for the perception of movement in depth. The method of constant stimuli was regarded as eliminating certain methodological difficulties noted in earlier experiments of Smith, incident to the use of the method of limits. In the method of constant stimuli it is customary to use at least 5 stimulus values, with a large number of instances of each value being presented in random order. A record is kept of the percentage of reports in which the subject detects the psychological phenomenon being investigated. From the cumulative probability curve fitted to the data, one can specify the threshold as the stimulus value corresponding to a specified percentage of positive reports recorded on the cumulative percentage axis. In Baker and Steedman's application of this method, they used as their stimulus variable the time of exposure of the moving stimulus. This variable could also be expressed as the equivalent distance of travel of the stimulus-object, for a given velocity of the stimulus object, and as an increment, positive or negative, in the visual angle subtended at the eye. As an index of the threshold, the authors used the 75% point on the cumulative frequency axis, rather than the 50% point.

With this threshold value, the authors were now in a position to investigate the effect of various parameters. The authors report the following effects:

(a) as the luminance of the stimulus target increases, the threshold decreases;

(b) as the velocity of the target increases, the threshold decreases; and

(c) when the target is viewed binocularly, instead of monocularly, the threshold decreases.

This decrease in the threshold is regarded as equivalent to an increased capability for detection of movement in range.

The magnitude of the visual angle change required for threshold level to be reached is of interest. At a luminance level of 1 ft. lambert, it was found that a 2% change in visual angle was required to reach the 75% level on the curve. Since the initial visual angle was always 40 min. of arc, this increment is equivalent to a visual angle of 0.8 min. of arc, somewhat less than the customary specification for visual acuity of 1 min. of arc. The authors raise the question of whether the 2% value or the equivalent 0.8 min. of arc is the significant quantity to be used, if one wishes to extrapolate to different initial values of the subtended visual angle.

To answer this question, the authors carried out another investigation, in which the initial visual angle of the visual target at the first instant of exposure was made to vary between 1.5 and 60 min. of arc (ref. 70). The function derived from the experimental data, showing the threshold angular increment required as a function of initial subtended angle was approximately 8% for small initial angles (1.5 min. of arc) and 2% at large initial angles (60 min. of arc), with a continuous curve connecting these two points. Thus for small visual angles, the requirement of a minimum visual angle increment was determining; for larger visual angles, the percentage requirement gradually took over. There was evidence of a break in the curve at about the 12 min. point on the curve, suggesting to the authors the operation of two separate mechanisms in the response system.

Baker and Steedman were thus able to derive quantitative data for representing the ability of subjects to detect movement in range, presumably on the basis of detection of visual-angle increments; but it is not obvious how specification in such threshold terms can be converted to the specification of velocities, as required for rendezvous operations. It is a task for future development to determine whether information of this kind can be obtained. As an initial goal, it would be of interest to design experiments with the objective of obtaining error-data such as was obtained in the long range investigations of absolute distance perception. Two procedures suggest themselves: (1) training procedures leading to tests of the ability to estimate velocities in range, in ft. per sec. or the like; and (2) matching procedures analogous to those used by the Ames group for obtaining numbers to attach to perceptions of movement in range.

<u>Perception of simulated movements in range</u>. - The earliest investigations of perceptions of movements in range were reported from Metzger's laboratory at the University of Berlin in 1934, in the setting of Gestalt psychology. There is one paper by Metzger himself on the effect of shadows changing in size and shape in producing the appearance of movements in depth (ref. 55), and the report of an extensive investigation by Calavrezo (ref. 12) on the effect of various parameters on the perception of apparent movement in depth produced by the stroboscopic presentation of stimuli of different size and shapes. Calavrezo's investigation must thus be considered the first systematic investigation in this field. About 20 years later, Ittelson reported his investigation of radial movement, the term he used to designate apparent movement along an axis or radius extending from the subject to the perceived object (ref. 47).

In addition to the experiment reported in the previous section, Ittelson designed experiments to test the hypothesis that "assumed size" acts integratively with changes in visual angle to control the apparent distance of an object which appears to be moving in depth. It was found that differences in the "assumed size" of a test-object, brought about by differences in the visual pattern, were effective in eliciting changes in the apparent distance of the object, even when it was simultaneously undergoing apparent movement in range due to continuous changes in visual angle. The results were interpreted as lending additional support to the thesis that assumed size was an important cooperating factor in the mediation of apparent distance by visual angle cues.

The studies of Smith (ref. 67, 68, 69) were concerned with the determination of the sensitivity of the perception of "apparent movement in depth" to a number of variables. The technique adopted for producing perceptions of apparent movement in depth was that of changing the size of a stimulus-object (an equilateral triangle) located at a fixed distance from the subject. The rate of change of size (as given by the angle subtended at the eye by one side of the triangle) was not treated as an independent variable. It was a constant in all experiments.

The sensitivity of the observer to the perception of apparent movement in depth was measured by his reaction time. A shorter reaction time was regarded as indicating an increase in sensitivity. The observers were asked to report the first instant at which movement of the object in depth was seen. The independent variables investigated for their effect on sensitivity (i.e., on reaction time) were conditions that might ordinarily be designated as parameters: the "property of movement" (i.e., associated meanings); the tri-dimensionality of the object; the viewing procedure (monocular vs. binocular); the brightness of the object, as measured in units of luminance; and its apparent size, as measured by supplementary matching procedures.

The authors concluded that sensitivity to the perception of apparent movement in depth was: (1) increased by increases in the brightness of the visual target, and (2) by the use of binocular vision as compared with monocular vision. The other characteristics treated as independent variables were not found to have a significant effect on sensitivity.

Brightness as a Cue to Range Information

Because the inverse square law operates in space for point source targets it is possible to derive information concerning range, and perhaps range rate, from changes in the apparent brightness of a target such as a spacecraft beacon. For a constant source, brightness is sytematically related to range.

Absolute Range Judgements - By making estimates of absolute brightness it may be possible to derive judgements of absolute range. Taylor (ref. 73) describes a technique whereby absolute estimates of range could be derived by comparing the target with a standard, using a simple device for maintaining the level of adapatation relatively constant. In the space situation matches between the target and stars of known magnitudes can yield absolute range values with a minimum of additional computation. The astronauts have reported their observations of spacecraft beacons by stating that these beacons appeared as bright as specific stars of known magnitude. The accuracy and resolution of these matches is not known but could be calulated from flight data.

Wienke (ref. 79) performed a study to assess the capability of observers to make absolute judgements of luminance with the eye in a relatively constant state of dark adapatation. Observers were required to assign the correct designation to one of five stimuli. Over the range of stellar magnitudes from 2.30 to 5.33 he reports absolute discriminations could be made with almost 100 percent reliability if the stimuli were separated by approximately 1.40 stellar magnitude. These data indicate that judgements of absolute brightness are at best rather crude and of little utility as a means of estimating range. A technique which uses comparison stimuli would appear to be superior.

Brightness discrimination - Brightness thresholds can be used as a basis for judging range at two sucessive instances in time for estimating the range difference, or the perception of a changing brightness can be direct.

The available literature on thresholds for brightness discrimination is also of little value in establishing either the specific values or even the range of values for parameters to be investigated. This situation results, in part, from the common concern with relatively large fields rather than with a point source as used in the present beacon simulation. As Geldard (ref. 25) has reported, the effect of field size is critical since differential thresholds for small sources are considerably greater than comparable thresholds for extended sources. Many studies have employed simultaneous rather than successive presentation of test and comparison fields. In addition values presented for judgement are generally held fixed. As a consequence, generalizations from typical studies are inappropriate for judging range in a dynamic situation.

The effect of rate of brightness change has been investigated by Drew (ref. 19) whose conslusion that differential thresholds increase with decreasing rates of change is in direct contrast with results reported by Connors (ref. 15).

In Connors experiment the discrimination of brightness differences was studied in relation to the rate of brightness change and the initial level of brightness of a point source. A constant rate of one flash per second and an "on" time of 10 percent were employed. As previously suggested, results showed that the slower rates of change in fact produced lower thresholds.

The results of a study performed under the present contract (ref. 5) indicated that the thresholds for brightness increase were positively related to the rate at which the brightness of the beacon increased. In this respect the results are in exact agreement with those previously reported by Connors (ref. 15), who concentrated, in her investigation, on higher rates of of brightness change extending to approximately 200 times the lower limit of the present experiment. The same type of relationship between rate of brightness change and discrimination thresholds has been found to hold over a range of rates of brightness increase of some 200 to one. Although subjects required more time to discriminate brightness changes when the rate of change was slow, the actual increase in brightness was lower for those slower rates.

The obtained data indicated that thresholds obtained in the present study were of a magnitude far greater than those typically encountered in the literature on brightness discrimination.

Geldard (ref. 25) reports differential thresholds that run from approximately -2.0 to 0.0 log units. For the rate of brightness increase and initial brightness level most closely resembling those used in the present study, Connors (ref. 15) found a median differential threshold of .279 log units compared with the .451 obtained in this experiment.

These differences may be due to procedural effects. The conservative procedures employed by us were chosen to reduce the variability in judgment which was anticipated for this rather ambiguous task. In addition, for practical purposes, it was desired to obtain limiting rather than optimistic estimates of the capability of humans for making the type of judgments involved.

A less prominent, but statistically significant relationship was also found between initial level of beacon illuminance and discrimination thresholds. The higher the initial illuminance, the shorter the discrimination time. Thus, to reduce the time required to discriminate brightness increases, provide a beacon with as high an luminance as is consistent with other design constraints. In the present experiment, a nearly ninefold increase in initial beacon luminance produced a 32 per cent reduction in the mean time required to discriminate an increase in brightness. Several reports suggested that flash rate and flash duration were relatively unimportant with regard to the initial detection of flashing beacons. Over the ranges studied, the results of the present study indicate that these same variables are also unimportant for the discrimination of increases in the brightness of flashing beacons.

In the study we conducted observers were asked to describe the criteria they had developed for making consistent judgements of increased brightness. Although nine different techniques were reported only two were

1. Increase in brightness of beacon relative to brightness of dots in adaptation field (which could represent stars)

2. Increase in the length of "rays" emitted by the beacon

The observer's preference for relative judgments is obvious, although this preference was certainly expressed in a variety of ways.

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VISUAL AIDS FOR SPACE NAVIGATION

This section contains brief descriptions of those devices which may be employed in visual space navigation and other space observation tasks. Instruments for observations on planetary surfaces are also discussed.

Windows may also be considered as instruments. However, no discussions of windows is provided here since windows are discussed in detail elsewhere in this report. Visors are also not discussed, except in relation to specific instruments.

Not all the devices discussed are presently available or contemplated for space use. However, all which are included here are considered to have potential for space use and worthy of further investigation. Many of the devices and visual factors described have been studied extensively but are included here in order to provide as comprehensive a list as possible, although the list is by no means complete, and to stimulate further those who may not be familiar with such devices.

Telescopes. - Several telescopes are called for in present space programs. The Apollo Scanning Telescope is an integrally mounted, servo driven telescope which is used in tracking navigational landmarks and as a view finder for the Apollo Sextant. The telescope provides no magnification but has a sixty degree field of view and a pair of crosshairs which may be aligned with a star or landmark. As a view finder, the task involved is to lay the crosshairs on a star with sufficient accuracy to bring the sextant, which is slaved to the telescope axis and has a one degree field, into play. Manipulation of the telescope is by means of hand operated servo controls. (Although it may also be computer controlled.) In landmark tracking, the crosshairs are placed on the landmark and computer based information is used to track the landmark automatically. However, the computed data may be inaccurate and cause drift. The computer data is then updated whenever the astronaut corrects the tracking rate to eliminate the drift of the crosshairs from the landmark.

The Lunar Excursion Module Alignment Optical Telescope also has a sixty degree field and crosshairs. However, it is not servo operated and can only be aimed in three discrete directions. In addition to the crosshair reticle, it also has a spiral reticle. This makes a single turn and originates at the center of the field and terminates at the edge of the field. Thus, when the Lunar Module is sitting on the surface, the crew can make a star sighting by rotating the crosshair and spiral reticle so that the spiral and one of the crosshairs intersect at the star.

Another telescope of note is planned for use with the Apollo Telescope Mount for orbital astronomical observation such as in heliography. Here, observations will be made with the use of high resolution television monitors within the spacecraft.

An additional type of telescope is the Lunar Module Docking Reticle. This is mounted and aimed through the ceiling above the astronaut's head and therefore requires him to bend his head backward to see through it in order to dock the Lunar Module with the Apollo Command Module. Crosshairs are provided which must be aligned, by positioning the Lunar Module itself, with a target on the Command Module, both in rotation and translation.

Telescopic driftmeters may also be considered for future spacecraft. These provide a grid of parallel lines which must be aligned with the apparent streaming of the planetary surface as the vehicle orbits.

Periscopes. - At this writing, no periscopes are known to be contemplated in presently planned space vehicles. One was used in the Mercury capsule. One periscope which has been proposed would permit the entire planetary horizon to be viewed at once and compared with a circular reticle. Once these are made concentric, the direction of the local vertical is established. The altitude is also obtained if the apparent diameters are identical and the size of the circular reticle is known. The proposed concept would include expanding the horizon portion of the image, by optically removing or compressing the central portion of the field, to exaggerate horizon movement. Other periscopes have been proposed for use in driving lunar vehicles.

Sextants. - Some variation of the marine sextant will probably be carried on most space missions, at least for backup navigation requirements. use of the common sextant involves the superposition of two object images, usually a star and a landmark. The image of the landmark is usually seen directly through a partial mirror. The star is seen as a reflection from the partial mirror. An auxiliary mirror is generally used to direct the light from the star to the partial mirror. The angle of the auxiliary mirror is varied to align the two images and measured to obtain the reading. Magnification of the images may be provided.

The Apollo Command Module Sextant is understood to be not a sextant but actually a servo driven, 28 power telescope. It is apparently used by aiming it at one object, reading the angle of regard with respect to one vehicle axis and then repeating the process with another object. The two angles must then be added. It is mounted integrally with the Apollo Scanning Telescope and is controlled together with the Scanning Telescope.

Rangefinders. - Plans to employ rangefinders in space are not known at the present time. There are four types of optical rangefinders: The split image, the dual image, the stereo and the stadiometric.

The split image rangefinder involves two mirrors separated by a known distance. One mirror masks out half the scene seen by the eye and also reflects the light transmitted from the other mirror (as in a periscope) to complete the scene. The angle of one of the mirrors is varied to make the upper or lower half of the scene, seen directly, match the other half, seen via the mirrors.

The dual image type is similar to the split image type except that a partially reflecting mirror replaces the half mirror. Thus, two whole images are seen, a steady image and a movable image, until they are brought into coincidence by varying the mirror angle.

Stereo rangefinders are considerably more complex and require the simultaneous use of both eyes. Optical tricks are employed within the rangefinder lens system to cause the eye to perceive a patterned reticle as being at the same range as, or at a greater or lesser range than, the target through stereopsis.

Stadiometric rangefinders differ from the preceding types in that the height (or other dimension) of the target must be known. The angle subtended at the eye is then measured with the stadiometer, which is actually a specially designed sextant, which provides a direct reading in range. Generally, however, the two images of the object are not superimposed, as in a sextant or dual image rangefinder, but are "stacked" so that the edge of one image is just touching the opposite edge of the other, in the direction of the known dimension.

Binoculars. - Binoculars may be used on space missions. If used, they are most likely to be used on exploratory extravehicular surface missions by helmeted astronauts. Hand telescopes are also a possibility. Surveying and other precise observations will probably be conducted from vehicle mounted equipment.

Binocular viewers. - A type of binocular viewer has been proposed which permits an astronaut to see both a reseau (or grid) and the external scene at the same time. Different reseaux would be available which would permit: (a) matching the curvature of the horizon to determine spacecraft altitude (and the direction of the local vertical); (b) finding the radiant point (perspective origin) from which all distant objects appear to stream due to spacecraft motion; (c) taking bearings to landmarks from the direction of ground track; and (d) timing the transit of the spacecraft over landmarks. The description of these novel techniques must be omitted here for the sake of brevity.

Head's up displays. - These displays provide a reticle, or other information, which can be seen superimposed upon the real world at which the crew member is looking. Such a device has been considered for the Apollo Command Module although its purpose is not known at this writing. Frequently, head's up displays are obtained by reflecting an image from a cathode ray tube (CRT) off of the vehicle window. Thus, when a computer driven "blip" from the CRT is aligned with the target by moving the vehicle, the pilot has aimed the vehicle correctly for the intended action, as determined by the computer.

Cathode ray tube (CRT) displays. - In addition to the head's up displays, other CRT type displays may be employed for external observations. These might be derived from television, low-light-level television, infra-red television and synthetic data. The latter might be obtained by computer and combined with the televised information.

Film strip aids. - These might be used in conjunction with direct visual observation as a means of making estimates of navigational position. They might comprise photographs of target areas and serve as memory aids in finding unfamiliar areas.

Embossed film strips. - These would provide miniature relief maps of the desired area, as above.

Foster's eye. - This proposed device is based upon the principal that two hemispheres, one half the radius of the other, demented back-to-back, provide a groundglass view of the external field upon the surface of the larger sphere. With a proper grid, this surface can be used to measure angular relationships between objects in the angular field.

CONCLUSIONS AND RECOMMENDATIONS

To ask for conclusions and recommendations based on the results of the effort conducted to date is to ask first for an analysis of the successes and limitations of the study itself.

The effort might be summarized by the paradoxical statement that we have dug deep and yet only scratched the surface. Clearly there is an enormous mass of data. In the particular areas selected for emphasis, namely, the physical environment, visual sensitivity, motion perception and distance perception we have made a rather comprehensive survey of the available data. This survey has been conducted with emphasis on the practical applications and lacks theoretical framework, and detailed scrutiny of more academic endeavors. What we intended to provide, and what we feel we have provided is a data base, an indication of relevant phenomena, and some insights into the source and the application of the data. With some misgivings due to practical constraints we must, at present, leave the potential user to evaluate the relevancy of these data to specific problems.

In retrospect, when considering sensitivity and cross range motion, we have essentially limited this survey to sensing of point source targets against fairly uniform backgrounds. With respect to range determinations we find most data deals with extended targets. The immediately apparent requirement is to consider extended targets and heterogeneous backgrounds. We have paid only cursory attention to the nature of information sensing using various optical aids. We have not attempted to operate systematically upon the available data in order to derive more general relationships. The need for evaluation of performance capabilities in utilizing optical devices and visual aids has only been mentioned. All of these things should be accomplished.

Within each particular area of investigation we find there are phenomena which are inadequately studied from the point of a basic understanding of the phenomena, and in almost all areas we see the need for the development of techniques which would make the data more useful in the applied situation. Perhaps the greatest limitation in all cases is the lack of a single integrated technique for evaluating the joint effects of relevant phenomena.

One of the greatest limitations on the overall availability of information is that most of it is conducted under static rather than dynamic conditions. Furthermore, the data is typically obtained in isolation, with only one, two, or three factors manipulated experimentally. The subject has no other task than to make the particular judgment called for. Some allowances must be made for the stresses of the operational situation.

In a related vein is the fact that complex, rather than simple judgments are required in practice but are not studied. Thus, as was pointed out with respect to range and cross range motion cues, the practical question most frequently involves a complex judgment of both values from a single target, while the laboratory studies treat of each in isolation.

While applicable data can be derived from more or less classical experimental procedures it is only through simulation of the operational situation that realistic estimates can be reliably obtained. These studies often do not yield generally applicable data because they involve a combination of conditions representing a confounding of the effects of a number of variables. Basic studies can often serve to establish rough parametric envelopes determining the range of conditions which should be tested in the simulation environment.

Within the three areas where a detailed investigation was conducted the following limitations and recommendations are made:

Physical environment. - The reflecting characteristics of specular and diffuse surfaces illuminated by collimated light (e.g., sunlight) remains one of the least understood aspects of the physical situation. It represents one of great practical importance in defining such things as detection ranges and visibility which are of obvious significance in planning mission operations as well as vehicle design. The selection of optimum coating characteristics for various mission situations could be a result of this study.

Once an equation is derived describing illuminance at the eye resulting from various sources in the visual field, it seems a reasonable step to conduct an error analysis of these equations. One could evaluate, much as in a guidance system, the effect of the variability or error in each parameter as it affects the accuracy of the judgment made relative to the inci-illuminance.

The operational flight data that has been included is only that which was available in the Gemini mission reports. It is, therefore, only a small part of the available data. The pilot and mission debriefing reports are the only complete source of operational flight data. It is recommended that they be studied and combined with a more thorough survey of the operational situation in much the same way as conventional flight test data is treated. The results of such a detailed study would be to accurately assess the validity of the analysis methods presented, to validate design and operation decisions made on the basis of conventionally acquired data, and thus to provide a solid basis for defining operational procedures and performance capability envelopes critical to systems design.

Visual sensitivity. - The sensitivity of the eye in steady state illuminations can be fairly well defined. There is a certain degree of inadequacy in the data describing changes in sensitivity to intermediate level of illumination, particularly with respect to the variation in rate of change in sensitivity as a function of the preceding state of adaptation and the existing ambient.

There was no data which we found dealing systematically with the response of the eye to a series of illumination transients. It would appear that methods of analysis such as are used in control systems analysis could be fruitfully applied to the modeling of the dark adaptation process where the input functions consist of non-periodic inputs varying in amplitude, duration and waveform.

We find that there is no precise data available on the inflight cabin illumination levels and on a number of flights little attention was paid to carefully establishing adaptation levels for optimum target acquisition. In planning missions, attention should be paid to the variability in individual sensitivity and empirical tests on the astronaut population would probably be most valuable. In particular adaptation under ambient operational illumination conditions requires study.

Target search and acquisition, as currently required, occurs in practical situations with highly trained observers who know where to look.

Thus, effective contrast of target and background become the primary determinant of detection range. Empirical relationships in this area are fairly well defined.

Cross range motion. - The problems of establishing performance capabilities with respect to the detection and utilization of cross range motion lie in the requirement to specify the explicit stimulus conditions and operational situations in which the requisite judgments are to be made. Although a degree of consistency is exhibited in the available literature, the conditions under which the measurements are made appear to exercise a major effect on the threshold values. With respect to line of sight nulling techniques, the most directly relevant studies used an inadequate number of subjects and permitted lengthy observation times. The level of training of the observer was also unclear. In our judgment a more exact derivation of operationally realistic values can be obtained through establishment of an adequate test environment, using observers who are trained with respect to star pattern recognition and operational procedures. Factors such as adaptation levels, accurate starfields, and target rates of motion must be realistically stimulated.

In emphasizing the need to accurately recreate the probable operational situation it should be clearly recognized that little, if any, data were obtained with respect to simulation judgment of target motion relative to more than one axis. This area obviously requires consideration, perhaps first on the basis of an assumption that composite motion can be readily resolved into the two or three orthogonal planes.

Consider further that almost all experimental data involves the simplest form of straight line motion. Very little has been done with respect to target undergoing acceleration or deceleration, or with moving along the complex relative motion paths typical of spacecraft maneuvers.

Range and range rate. - Some of the most marked limitations in existent research lie in the field of the absolute perception of depth. Verbal estimates of absolute distance provide a translation of visual perception into a number, a form of report readily usable in rendezvous control operations. There are, however, serious limitations to the data obtained in this form. (1) The estimates are subject to large constant and variable errors. But there has been no systematic work reported in which the possibility of decreasing these errors appreciably by training and observer-selection has been investigated. There is need, therefore, for studies on individual differences in the magnitude of these errors and on the effect of training procedures. (2) The targets so far used have been extended sources. Studies are needed of sources approximating point-sources in appearance, viewed in a field without other objects, and with various backgrounds of the types that may occur in space operations. (3) The ranges used have been limited compared to those involved in rendezvous operations. Studies are needed at larger ranges in empty field situations. But such studies do not seem feasible except by means of simulation methods. There is need therefore for establishing the validity of simulation techniques for representing objects at large ranges. (4) An alternative method for obtaining numbers to represent absolute distance is through the use of the psycho-physical method of equivalents, involving distance-matching or comparison fields. There is need, therefore, to determine the extent to which comparison procedures, such as have already been used at short distances in studies of the role of various cues to depth, can be implemented at larger distances. Such translation to larger ranges suggests the need of optically simulated distances of the comparison-objects by means of techniques such as stereoscopy or virtual imagery.

In the field of relative depth-perception, there is need for comparative data on the magnitude of depth-thresholds when two objects are presented successively in time rather than simultaneously. In the typical investigation of relative depth-perception, simultaneous presentation of stimulus-objects is used. In rendezvous operations, however, data obtained from successive comparisons may be more appropriate, since the astronaut observing a single spacecraft is in a position to make relative judgments of distance only on the basis of successive views of the other vehicle. The effect of temporally discrete visual fields as compared with continuously changing fields on difference thresholds also needs investigation.

In any situation in which two objects are compared, either in successive or in simultaneous comparisons, constant errors known as space and time-errors may be involved. Although such errors have occasionally been invoked as offering possible explanations of puzzling results, there has been no systematic investigation of the extent to which such errors may be involved in errors of over-and under-estimation. In rendezvous operations, there will probably not be sufficient time to utilize the classical psychophysical methods for eliminating such errors. Some previous exploratory work of the writer indicated that there are large individual differences in such errors; hence the need for establishing their magnitude and consistency for a given observer.

The investigations of relative depth-perception, based on discrete successive presentations of a given field of view, merges with that of perceived movements in range, which involves the perception of continuous change. Only a beginning has been made in this field, with judgments of observers limited to perceptions of direction of movement, and of the phenomenological similarity of movements generated by different techniques. To provide data more directly usable in rendezvous operations, information concerning the velocity of movements perceived is desirable. The whole gamut of possible investigation of perceptions of velocity, and of the possibility of obtaining numerical specification of velocities, is therefore needed. Some examples of key problems, as yet unexplored, are: (1) Determine difference-thresholds for perception of the velocity of movement in range, in addition to stimulus-thresholds, for each of the effective cues, in isolation and in combination, at various ranges; (2) Determine constant and variable errors in estimates of velocity, following an appropriate period of training; (3) Determine the feasibility of obtaining measurements of the velocity of movements in range on the basis of equivalence-methods, in which an unknown velocity is compared, by way of perception, with known velocities adjusted to perceptual equivalence. The results of studies such as these should permit us to assess the possibility of extracting velocity information from direct visual perception, and the extent to which optical aids, or direct physical measurement is essential.

TABLE I

RANGE OF PARAMETERS FOR
SELECTED GUIDANCE SCHEMES

Distance Zone	Parameter	Range of Parameter
1. Long range (500 to 20 n.mi.)	R, range to target	500 to 20 n.miles
	$\dot{R}$, range-rate	2000 to 100 ft/sec
	α, elevation angle of line-of-sight	-30 to 30 degrees
	β, azimuth angle of line-of-sight	-5 to 5 degrees
	$\dot{\alpha}$, elevation angular rate of L-O-S	-0.5 to 0.5 deg/sec
	$\dot{\beta}$, azimuth angular rate of L-O-S	-0.5 to 0.5 deg/sec
2. Medium range (50 to 2 n.mi.)	R,	50 to 2 n.miles
	$\dot{R}$,	500 to 20 ft/sec
	α,	$\pm$ 0 to 60 degrees
	β,	-30 to +30 degrees
	$\dot{\alpha}$,	-0.5 to 0.5 deg/sec
	$\dot{\beta}$,	-0.5 to 0.5 deg/sec
3. Short range (5 n.m. to 100 ft.)	R,	5 nm to 100 ft.
	$\dot{R}$,	100 to 0 ft/sec
	α,	$\pm$ 90 to $\pm$ 180 deg
	β,	$\pm$ 20 to $\pm$ 90 deg
	$\dot{\alpha}$,	$\pm$ 1 to $\pm$ 10 deg/sec
	$\dot{\beta}$,	$\pm$ 1 to $\pm$ 10 deg/sec

Table II

EQUATIONS OF MOTION*

Guidance Scheme #1:

$$\ddot{R} + \frac{\mu R}{\rho_t^3} - \mu R_t \left(\frac{1}{R_t^3} - \frac{1}{\rho_t^3} \right) \sin\,(\theta_o - \omega_e t) = 0$$

$$- \mu R_t \left(\frac{1}{R_t^3} - \frac{1}{\rho_t^3} \right) \cos\,(\theta_o - \omega_e t) = \frac{T_n}{m_c}$$

Guidance Scheme #2:

$$\ddot{R} - R\omega_e^2 + \frac{\mu R}{\rho_t^3} - \mu R_t \left(\frac{1}{R_t^3} - \frac{1}{\rho_t^3} \right) \sin\theta = 0$$

$$2\dot{R}\omega_e - \mu R_t \left(\frac{1}{R_t^3} - \frac{1}{\rho_t^3} \right) \cos\theta = \frac{T_n}{m_c}$$

where:

R = relative distance between target and chaser

ω_e = earth rotation frequency

R_t = target distance from orbit center

ρ_t = chaser distance from target orbit center

θ = local angle of chaser with respect to local horizontal thru target

σ_o = initial σ

μ = gravitational constant

t = time

T_n = thrust vector + to R

m_c = chaser mass

*From reference (20).

TABLE III

TECHNIQUES FOR OBTAINING SELECTED GUIDANCE PARAMETERS

No.	Parameter	Ref.	Procedure
1	$R, \dot{R}$		1. Align chaser so thrust vector is perpendicular to L-O-S (line of sight). 2. Note two readings of L-O-S angle for a 10 second interval. 3. Apply known thrust acceleration to arrest L-O-S rate. 4. Note thrust time and final L-O-S angle. 5. Calculate R and $\dot{R}$ from formulas.
2	R		1. Count number of visually detectable light pulses from target (known sequence of pulses).
3	$\dot{R}$		1. Take range measurements at noted time intervals. 2. Approximate $\dot{R}$ as $\frac{\Delta R}{\Delta t}$, average over several samples.
4	α, β		1. Point vehicle so it is boresighted on target. 2. Read angles from inertial 8-ball or IMU referenced to inertial coordinates.
5	α, β		1. Read angle from target to known stars with sextant.
6	α, β		1. Read angles from target to horizon with sextant or window reticle.
7	$\dot{\alpha}, \dot{\beta}$		1. Using α, β data from above techniques, approximate α, β as $\frac{\Delta X}{\Delta t}$ $\frac{\Delta\beta}{\Delta t}$.
8	$\dot{\alpha}, \dot{\beta}$		1. Null apparent motion against stars.

TABLE IV - TYPICAL BACKGROUND LUMINANCE SOURCES AND THEIR LUMINANCE[a]

Background Luminance Source	Information Source	Background Luminance	Threshold Illuminance (Blackwell)
Zenith sky @ night w/full moon	Huch & Ney	$1.18(10)^{-3}$ ft.L	$2.8(10)^{-8}\ \frac{lum}{m^2}$
Avg. nighttime sky away from milky way	Huch & Ney	$2.34(10)^{-5}$ ft.L	$4(10)^{-9}\ \frac{lum}{m^2}$
Full earth (sunlit)	Connors	$5.0(10)^{3}$ ft.L	$2.2(10)^{-3}\ \frac{lum}{m^2}$
Full earth (moonlit)	Connors	$5.0(10)^{-3}$ ft.L	$3.0(10)^{-8}\ \frac{lum}{m^2}$
Window luminance (~ 1%) scatter	Huch & Ney		
sunlit	Connors	$1.26(10)^{2}$ ft.L	$2.2(10)^{-5}\ \frac{lum}{m^2}$
earthlit		$5.0(10)^{1}$ ft.L	$1.8(10)^{-5}\ \frac{lum}{m^2}$
moonlit		$1.26(10)^{-4}$ ft.L	$1.0(10)^{-8}\ \frac{lum}{m^2}$
Spacecraft Corona (Avg) (solar illum.)	Huch & Ney	$5.81(10)^{-1}$ ft.L	$1.4(10)^{-7}\ \frac{lum}{m^2}$
Cabin lights	Schmidt	$1.0\text{-}2.0(10)^{1}$ ft.L.	$3.0(10)^{-6}\ \frac{lum}{m^2}$ $6.0(10)^{-6}\ \frac{lum}{m^2}$
Earth Airglow	Schmidt	$1.14(10)^{-2}$ ft.L	$3.2(10)^{-8}\ \frac{lum}{m^2}$

a-Values are for 100% probability of detection of a steady point source light against the given background.

TABLE V - STELLAR MAGNITUDE AND THEIR CORRESPONDING EARTH SEA LEVEL ILLUMINANCE

Magnitude	E (lumens/Km^2)	Log E	Magnitude	E (lumens/Km^2)	Log E
-5	264	2.422	2	0.418	$\bar{1}.621$
-4	105	2.021	3	.1665	$\bar{1}.221$
-3	41.8	1.621	4	.0663	$\bar{2}.821$
-2	16.65	1.221	5	.0264	$\bar{2}.422$
-1	6.63	.821	6	.0105	$\bar{2}.021$
0	2.64	.422	7	.00418	$\bar{3}.621$
1	1.05	$\bar{1}.021$	8	.001665	$\bar{3}.221$

TABLE VI – THE PHOTOMETRIC CHARACTERISTICS OF PLATES OR DISCS, SPHERES, CYLINDERS AND CONES

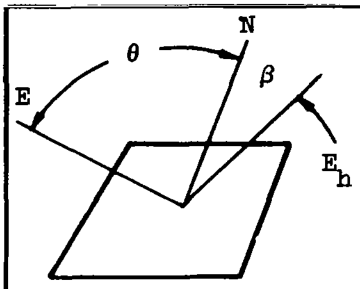
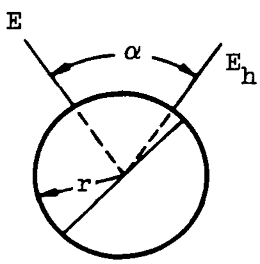
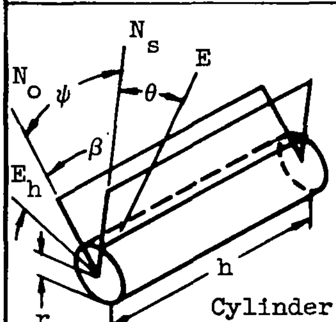
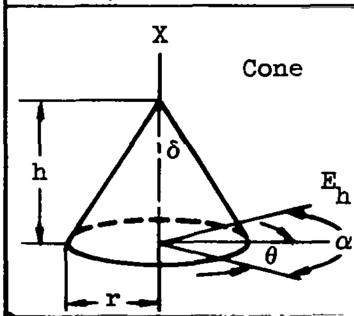
	(footcandles)	Ba (foot lamberts)
 Plate	$\rho_r E_o \tau \frac{A_p}{D^2} \cos\theta \cos\beta_i$	$\rho_r E \tau \cos\theta_i$
 Sphere	$\frac{2}{3} \rho_r \tau E_o \left(\frac{r}{D}\right)^2 \left[(\pi - \alpha_i) \cdot \cos\alpha_i + \sin\alpha_i\right]$	$\frac{2}{3} \rho_r \tau E$
 Cylinder	$\frac{1}{2} \rho_r E_o \tau \left(\frac{rh}{D^2}\right) \left[(\pi - \psi) \cdot \cos\psi + \sin\psi\right] \cos\theta_i \cdot \cos\beta_i$	$\frac{1}{2} \rho_r \tau E \cos\theta_i$
	$\frac{1}{4} \rho_r \tau E_o \left(\frac{h}{D}\right)^2 \sin\delta_c \left[(\pi - \alpha_i) \cos\alpha_i + \sin\alpha_i\right]$	$\frac{1}{4} \rho_r \tau E \cos\theta_i$

TABLE VII - SPACE VEHICLE SURFACE COATINGS AND THEIR APPROXIMATE REFLECTIVITIES

Vehicle	Reflective Coating	Approximate Reflectivity
CM	Z-93-W	0.85
SM	G.T.Schjedahl Co. (Specular) (+ Z93W)	0.70 (+ 0.85)
LM	ALZAC	0.80
SIVB	Z93W (proposed)	0.85
Gemini	Z93W	0.85
Agena	Diffuse White (+Specular Surfaces)	0.85 (+0.70)
ATDA	Z93W	0.85

TABLE VIII - RUNNING LIGHT CHARACTERISTICS FOR APOLLO AND GEMINI VEHICLES

Vehicle	Color	Output Intensity
CM and SM	Green	.6 Candles
	Red	.6 Candles
	Amber	.6 Candles
LM	Green	.20 Candles
	Red	.20 Candles
	Amber	.37 Candles
	White	.37 Candles
GEMINI	Red	.3 Candles
	Amber	.3 Candles
	Green	.3 Candles

TABLE IX - GEMINI AND APOLLO VEHICLES
ACQUISITION BEACON CHARACTERISTICS

Mission and/or Vehicle	Beacon Output ($I_f t_p$)	Beacon Intensity (I)
GT VI	40 cd-sec	190 cd.
GT VII	40 cd-sec	190 cd.
GT VIII	80 cd-sec	380 cd.
GT IX	80 cd-sec	380 cd.
GT X	150 cd-sec	715 cd.
GT XI	150 cd-sec	715 cd.
GT XII	170 cd-sec	810 cd.
CM	Unknown	-
S IV B	270 cd-sec	1285 cd.
LEM	750 cd-sec	3570 cd.

TABLE X - SPACECRAFT WINDOW CHARACTERISTICS

Spacecraft	% Transmission (preflight)	% Scatter (preflight)	Approximate % Trans. (postflight)	% Scatter (postflight)	Window Size (Angular)
Gemini	87%	1 - 2%	25 - 80%	Unknown	$72^\circ \times 41^\circ$
CM	93%	1 - 2%	35 - 80%	10 - 50%	$35^\circ \times 39^\circ$(rendezvous) $35^\circ \times 6^\circ$(side)
LM	76-87%	Unknown	Unknown	Unknown	$74^\circ \times 96^\circ$

TABLE XI - GUIDANCE AND NAVIGATION SUBSYSTEM OPTICS AND LM ALIGNMENT OPTICAL TELESCOPE (AOT) OPTICAL CHARACTERISTICS

Vehicle	Optics	Field of View	Magnification
Apollo	Scanning Telescope	60°	Unity
	Sextant	1.8°	28
LM	AOT	60°	Unity

TABLE XII - OPERATIONAL FLIGHT EXPERIENCE DATA

Flight	Time (Min) (From Sun-set)	Sighting Distance	Target Il-lumination	Shape of Target	Target Int.	Lum. of Backgrd.	Percep-tion	Window Trans-mission	Adapt. Source
V	Daylight	-	-	Gemini Window	-	$1.45(10)^{2}$ ML	(Cabin Lt Measure) (2^{o} above Horizon)		- Black Sky
VI	-12 Min	54nm	Solar	GT VII	$4.28(10)^{5}$ CD	31.4 ML	Venus -4 Mag	.8	Cabin Light
VI	+7 Min	24 nm	ACQ Lights	-	$3.62(10)^{2}$ CD	$4.71(10)^{-1}$ ML	Barely Visible	.8	Still Adapt-ing
VII	Daylight	-	-	-		$4.71(10)^{1}$ ML	Stars not Visible	.7-.8	
VIII	0.0	45nm	ACQ Lights	-	$3.62(10)^{2}$ CD	$3.14(10)^{-2}$ ML	5th-6th Mag.Star	.7	Corona or Low Cabin Light
VIII	-20	76nm	Solar	GATV	$5(10)^{5}$ CD	20 ML	Just Vis-ible	.7	Cabin Light
VIII	+4	-	-	-	-	$1.22(10)^{-2}$ ML	Airglow Visible	.7	-
VIII	+4	-	-	-	+2 mag star	$1.22(10)^{-2}$ ML	Stars Visible	.7	-
VIII	-56	-	-	-	+2 mag star	$1.22(10)^{-2}$ ML	Stars Dis-appear	.7	-

TABLE XII - OPERATIONAL FLIGHT EXPERIENCE DATA (Cont'd)

Flight	Time (Min) (From Sunset)	Sighting Distance	Target Illumination	Shape of Target	Target Int.	Lum. of Backgrd.	Perception	Window Transmission	Adapt. Source
IX	-24	50 nm	Solar	ATDA	$1.29(10)^2$CD	$5(10)^{-4}$ML	Just Visible	.75	Corona or Low Cabin Light
IX	-45	24 nm	Solar	ATDA	$1.58(10)^5$CD	$6.28(10)^2$ML	Venus Bright	.75	Bright Window
IX	Earth Night Side	20 nm	ACQ Lights	-	$3.62(10)^2$CD	$2.04(10)^{-3}$ML	Just Visible	.75	Night Sky + Low Cabin Light

TABLE XIII

FUNCTIONAL CHARACTERISTICS OF THE RETINA
(After Stiles, ref. 44)

	Light-adapted State	Dark-adapted State
1	Occurs when the eyes have become adapted to a field brightness above about 10^{-3} candles/sq.ft.	Occurs when the eyes have become adapted to a field brightness below about 10^{-3} candles/sq.ft.
2	After being dark-adapted the eyes become light-adapted in a time of the order of two or three minutes, when the brightness is raised.	After being light-adapted, the eyes take a considerable time of the order of 30 min. or more to become dark-adapted when the brightness is lowered.
3	An object or a light signal is seen most easily when the view is directed towards the object. (The object is then said to be seen by foveal vision because the image of the object at the retina of the eye, falls on the central part known as the fovea.) Certain kinds of flickering light form an exception to this rule.	An object or light signal is seen most easily when the view is directed somewhat to the side of the object. (The object is then said to be seen by parafoveal vision, the retinal image being formed in the region immediately surrounding the fovea, known as the parafovea.) Light signals emitting only red light form an exception as they are seen equally well or possibly better by foveal than by parafoveal vision.
4	The eye is most sensitive to radiation of wavelength λ = approx. 555 $m\mu$ (foveal vision).	The eye is most sensitive to radiation of wavelength λ = approx. 515 $m\mu$ (extrafoveal vision).
5	Appreciation of colour is of the same general character at the fovea. and in the parafovea.	Except for red signals a signal can always be detected by extrafoveal vision, at a much lower intensity than that required for its colour to be appreciated. With foveal vision the intensity for the appreciation of colour is not greatly in excess of the threshold intensity.

TABLE XIV

CHANGES IN ABSOLUTE THRESHOLD OF THE DARK ADAPTED EYE AS A FUNCTION OF ILLUMINATION TRANSIENTS (log mmℓ)

(After Grant & Mote, ref. 24)

Measure	Experimental Condition				
	1.0 sec 1600 mℓ	0.1 sec 1600 mℓ	1.0sec 160 mℓ	0.1sec 160 mℓ	Control
Threshold Rise	.940	.236	.329	.029	-.018
Immediate Recovery	.286	.232	.322	.188	.133
4 Min. Recovery	.941	.313	.415	.106	.073
General level of adaptation	4.446	4.229	4.291	4.264	4.201

TABLE XV

EFFECTS OF PRE-EXPOSURE CONDITIONS ON THE COURSE OF SUBSEQUENT DARK ADAPTATION

(After Anderson, ref. 2)

Variable	1 Initial Threshold	2 Cone Slope	3 Cone Plateau	4 Rod-Cone Break	5 Rod Slope	6 Rod Final Level
Brightness	Increases initial threshold	Not systematic	Occurs later	Occurs later	Varies	No marked effect
Duration	Increases initial threshold	5 studies show increase - 1 shows decrease	Occurs later	Occurs later	Varies	Almost constant
Wavelength	Highest after red			Red has least effect		
	Similar hues in pre-exposure and adaptation have most marked effect.					
Size	No data	No change	No change	Occurs later	Decreases	Almost constant
Location	No data	--	--	--	--	--
Periodicity light time increases	Initial threshold increases	Decreases	Occurs later	Occurs later	Decreases	Constant
Time interval increases	No data					
No. of exposures	No data	--	--	--	--	--
Frequency/rate increases	No data	--	--	--	--	--

TABLE XVI

ABSOLUTE THRESHOLDS FOR THE DETECTION OF ANGULAR MOTION

Basic Studies

Threshold Value	Conditions: Duration	Intensity	References	Ref. No.
10 Sec./Sec.	16 Sec.	500 ML	Good	32
10 Sec./Sec.	Unlimited	1.0 Ft.L	None	40
13 Sec./Sec.	16 Sec.	500 ML	No Grid	32
13 Sec./Sec.	Unlimited	Daylight	-	40
24 Sec./Sec.	Unlimited	.005 Ft.L	None	40
28 Sec./Sec.	2.0	500 ML	No Grid	32
30 Sec./Sec.	16 Sec.	.016 ML	Grid	32
34 Sec./Sec.	Unlimited	-	-	40
40 Sec./Sec.	16 Sec.	.016	No Grid	32
44 Sec./Sec.	.5 Sec.	Daylight	Mono, Fovea	18
54 Sec./Sec.			None	1
1.4 Min/Sec.	2 Sec.	.005 ML	No Grid	21
1-2 Min/Sec.	"short"	Clear Visible	-	1
2.5 Min/Sec.	4 Sec.	-	Yes	18
2-6 Min/Sec.	-	-		6
4 Min/Sec.	.125 Sec.	500 ML	None	31
8 Min/Sec.	.125 Sec.	500 ML	None	31
10-20 Min/Sec.	-	Clear/Visible	None	1
10 Min/Sec.	-	Daylight	Mono, Foveal	7
13 Min/Sec.	.125 Sec.	500 ML	Grid	31
18 Min/Sec.			9° Periph	1
20 Min/Sec.	.05 Sec.	.026 mℓ	CRT	16
44 Min/Sec.	.125 Sec.	.016 mℓ	No Grid	31
48 Min/Sec.	.125 Sec.	.016 mℓ	No Grid	31

TABLE XVII

ABSOLUTE THRESHOLDS FOR DETECTION OF ANGULAR MOTION APPLIED STUDIES*

Threshold Value	Detection Time	Conditions	Ref. No.
.1 M rad/sec	10 Sec.	Good Stat. Reference	2
.1 M rad/sec	169 Sec.	No reticle, direct observation	5
.1 M rad/sec	220 Sec.	17° field of view	47
.2 M rad/sec	60 Sec.	5th mag. star, trained observer	47
.8 M rad/sec	15 Sec	6 star reference	47
.8 M rad/sec	24 Sec.	1 star reference	47
1.6 M rad/sec	50 Sec.	3 mag star, trained observer	47
2.4 M rad/sec	45 Sec.	17° field of view	47
3.2 M rad/sec	5 Sec.	6 star reference	47
3.2 M rad/sec	12 Sec.	1 star reference	46
4 M rad/sec	2 Sec.	2 lines moving apart	

*These studies are characterized by use of a broad field of view, a moving point source target, point source "star" references.

TABLE XVIII

STIMULUS CONDITIONS PRESENT IN MEASUREMENTS OF $\Delta\omega$ (Ref. 11)

Ref.	Spatial Relation of 1 and 2	Stimulus Frequency	Stimulus Objects	Direction of Motion	Field Extent (deg)	Observa-tional Distance (cm)
3	Separate	Repetitive	Black rectangle on edge of 2 white disks	Circular	6.4	200
6	Separate	Repetitive	Black square on white paper	Rectilin-ear upward	2.15-4.30	200
7	Separate	Repetitive	Black square on white paper	Rectilin-ear upward	2.15-4.30	200
50	Super-imposed	Single	Two needles per-pendicular to line of sight	Rectilin-ear to S's right	3.6-15.0	15.9
30	Adjacent	Single	Spot on oscillo-scope	Rectilin-ear to S's left	4.8	53.3
17	Separate	Repetitive	Black vertical lines on white paper	Rectilin-ear to S's right or left	5.72	50
24	Separate	Repetitive	Wallpaper with pattern of dots	Rectilin-ear down-ward	8.4	122
38	Adjacent	Single	Spot on oscillo-scope	Rectilin-ear hori-zontal	10.0	25.4
4	Separate	Repetitive	White dot on edge of 2 black disks	Circular	5.2	200

TABLE XIX

METHODOLOGY USED IN THE MEASUREMENTS OF $\Delta\omega$

(Ref. 11)

Ref.	Psychophysical Method	Measure of	No. of Speeds	No. of Ss	No. of Measurements per Speed per S	Total No. of Measurements	Speed Deg/sec Min	Speed Deg/sec Max
3	Limits	Mean	3	1	20	60	0.77	5.04
6	Limits	Mean	2	2	10	40	1.79	3.58
7	Limits	Mean	6	2	6	72	1.72	4.58
7	Limits	Mean	5	3	3	45	2.29	4.58
50	Constant stimuli (3.6° field)	Standard deviation	4	2	100	800	2.67	20.1
50	Constant stimuli (15° field)	Standard deviation	6	2	100	1200	2.67	36.1
30	Constant stimuli	Mean	7	18	--	--	0.15	10.2
17	Average error	Standard deviation	5	10	4	200	2.07	4.81
24	Average error	Standard deviation	1	24	10	240	4.80	4.80
38	Constant stimuli	Mean	7	10	30	2100	0.34	22.7
4	Average error	Standard deviation	5	10	50	2500	2.7	24.3

TABLE XX

ANGULAR RATE THRESHOLDS FOR TWO STIMULI MOVING IN OPPOSING DIRECTIONS

(ref. 34)

Initial Separation Angle	Angular Threshold Rate	% Deviation Between Two Observers
12°	$.474^\circ$	16.8
42°	$.615^\circ$	1.9
66°	1.025°	31.0
128°	1.680°	23.7

TABLE XXI

DIFFERENTIAL ANGULAR RATE THRESHOLDS AS A
FUNCTION OF METHOD OF PRESENTATION

(ref. 35)

Angular Rate %/sec	Mean (Approximate)		
	Heterodi-mensional	Isometric	Isochronal
25	.21	.13	.13
50	.19	.14	.10
80	.18	.10	.06
180	.16	.10	.05
260	.19	.10	.04
525	.18	.10	.04

TABLE XXII

DIFFERENCE THRESHOLDS FOR VELOCITY

Brandalise & Gottsdanker (Ref. 4)		Bourdon (Ref. 3)		Brown & Mize (Ref. 7)	
Rate	%	Rate	%	Rate	%
2.7	6.4	0.8	11.0	1.7	14.5
5.4	4.71	2.3	7.0	2.2	12.6
8.1	4.86	5.0	7.0	2.9	2.4
16.2	3.96			3.4	11.2
24.3	4.33			4.0	16.9
				4.6	7.4

TABLE XXIII

DELINEATION OF THE CUES OF DISTANCE
(ref. 17)

Cues	Definition	Requirements For Applicability	Applicability in Space
Linear Perspective	The eye observes as if looking into a bowl. Lines parallel to the axis of observation appear to converge in the distance. The position of an object on the wall of this bowl is a function of both the distance of the object along the line of sight, and its deviation away from the line of sight. The field of view will normally contain a number of elements which have a long, strong surge toward convergence at visual infinity, for example, a mountain range, a fence or a line of buildings. The association of an object with one or more of these elements will produce a very strong cue of both absolute and relative distance.	Requires a "rationally" organized field filled with objects at varying distances	Very limited
Size	If the observer is familiar with the size of an object, the change in the apparent size of the object with changes in distance will be a cue for the estimation of absolute distance.	Knowledge of real size of the object.	Yes
Binocular Parallax	Binocular parallax is often called binocular stereopsis or retinal disparity. When the two eyes are converged and focused at a given distance from the observer, objects at significantly different distances fall outside of the horopter (region of single vision) and are thus seen as double images. The magnitude of the sepaeation of the two images of the same object is used as a cue of the relative line of sight distance between the point where the eyes are focused and converged, and the location of the other object. Also, if the object is between the observer and where his eyes are converged, the left of the double images will be seen by the right eye and the right of the double images will be seen by the left eye. If the object is beyond the point where the eyes are converged the reverse relationship will hold true. Thus, this cue furnishes information as to which of two objects is the more distant, and incomplete information relative to the magnitude of the	Good stereoscopic vision	Yes

TABLE XXIII(Cont'd)

Cues	Definition	Requirements For Applicability	Applicability in Space
Binocular Parallax (Cont'd)	difference. Thus, if the distance of one of the objects were known (for example, if one was visual infinity) the distance of the other could be estimated absolutely.		
Motion Parallax	As objects move across the field of view, the angular velocity with which they appear to move is a function of the distance from the observer, the linear speed of the movement and the angle of attack. To the extent that the linear speed and the angle of attack are known this is a cue of absolute distance. If either the linear speed or the angle of attack are unknown or both, but the unknown one or both can be considered to be equal for two or more objects in the visual field, then motion parallax can be used as a cue of relative distance, but not as a cue of absolute distance.	A knowledge of the linear speed and the angle of attack of the movement.	Yes
Aerial Perspective	The attenuation of light by the atmosphere produces an absolute distance cue by imposing a haze that is progressively more dense with an increase in the distance from an observer. Thus a mountain range in the distance is more muted than hills in the foreground.	Applicable only for comparatively great distances through the atmosphere except under unusual conditions such as smog.	No
Convergence	Convergence, like binocular parallax, relies on the separation of the two eyes, and operates simultaneously with binocular parallax. However the term "convergence cue" is reserved for the sensations furnished by the muscles attached to the eyeball as they pull the eyes from parallel fixations to fixations which converge at the object being viewed. This is an absolute cue of distance.	Useful only within the first 20 or 30 feet.	Yes

TABLE XXIII (Cont'd)

Cues	Definition	Requirements For Applicability	Applicability in Space
Interposition	Interposition occurs when the view of one object is at least partially blocked by the view of another object. This is a very strong cue of relative distance, but is not always present.	Where interposition occurs it furnishes a very strong cue of the ordering, but not of the magnitude of distances.	Yes, but infrequently
Association	This is a hodge-podge category where the distance of an object is estimated by its association with another object or characteristic in the visual field for which the distance is known.	Only applicable where there is an object or characteristic of known distance associated.	Yes, but infrequently
Accommodation	The change in the focus of images as the eye accommodates for near and far distance furnishes a reliable cue of absolute distance within the first 20 feet. The hypothesized sensations from the ciliary muscle of the eye as the lens is accommodated had been often proposed as the source of this cue. It is not. There is little if any sensation from this muscle which is associated with accommodation.	Applicable only within the limits of accommodation infinity, which is about 20 feet.	Yes
Lights and Shadows	When the position of the light source is known, and the light rays are diverging, the differences in the length and angle of shadows throughout the visual field can furnish a cue of relative distance. When the light is parallel, only the effective extension of the cue of interposition by the shadowing of objects can be used as a cue of relative distance.	Requires a background against which can be cast.	Very limited

TABLE XXIV

ERRORS IN ESTIMATES OF ABSOLUTE DISTANCE

Investigator		Constant Errors					Variable Errors (Std. Dev.)				
		McKinney et al. (ref. 54) 1963	Pennington & Beasley (ref. 60) 1965		Dees (ref. 17) 1966		McKinney et al (ref. 54) 1963	Pennington & Beasley (ref. 60) 1965		Dees (ref. 17) 1966	
Actual Range	Cue	Size	Size		Stere-opsis	Paral-lax	Size	Size		Stere-opsis	Paral-lax
	Direct		Approach	Recede				Approach	Recede		
100 Ft	Error	-30%	+10%	+ 6%	+26.8%	+ 7.7%	43.8%	42%	14%	43.1%	23.97%
250 Ft	in	-28%	+30%	+17%	+27.3%	+14.72%	51.3%	43%	16%	44.1%	25.5 %
500 Ft	Per-	-42%	+40%	+13%	+27.6%	+20.3%	74.0%	57%	23%	48.2%	27.6 %
800 Ft	cent	-40%	+26%	+13%	+28.0%	+24.3%	59.5%	49%	26%	45.2%	28.0 %
100 Ft	Error	-30'	10'	6'	26.8'	7.7'	44'	42'	14'	43.1'	24.0'
250 Ft	in	-70'	75'	43'	68.2'	36.8'	128'	107.5'	40'	110.2'	63.7'
500 Ft	Feet	-210'	200'	65'	138'	101.5'	370'	285'	115'	241.0'	137.2'
800 Ft		-320'	208'	104'	224'	194.4'	476'	392'	208'	361.0'	224.0'

TABLE XXV

SUPPLEMENTAL CONDITIONS IN INVESTIGATIONS OF ESTIMATED ABSOLUTE DISTANCE

Experimental Conditions			Investigators		
			McKinney, et. al. (ref. 54)	Pennington & Beasley (ref. 60)	Dees (ref. 17)
Depth Cue			Size	Size	Stereopsis, Movement-Parallax
Target Properties	Shape		Circular disc. Outline of man	Disc Triangle Cylinders	Disc (ping pong ball)
	Size	Linear Extent	Disc: 3' diam. Man: 6'2" tall	Disc: 1' diam.	
		Visual Angle			1.994°
	Luminance			From .007 to .14 candles per sq. ft.	11.35 candles per sq. ft.
	Duration of Exposure		At observer's volition		10 Sec.
	Background		Black	Black	Starfield (Lum. less than .032 candles per sq. ft.)
	Physical Distance		100;250;500;800 feet	0 to 1300 ft.	1 to 4000 ft. (simulated)
Observer Conditions	N		10	6	12
	No. of eyes (Binocular or Monocular)		Probably Binocular	Probably Binocular	Monocular and Binocular
	Refractive Conditions		20/20 Vision	20/20 Vision or better	20/20 Vision (corrected)

TABLE XXVI

TERMS USED FOR DISTANCE AND SIZE

Adjective	Variable	Approximate Equivalents
Physical	Size or Distance	Real, Actual
Apparent	Size or Distance	Perceived Experienced Phenomonological Estimated Inferred Judged
Assumed	Size or Distance	Corresponding to a particular meaning Corresponding to a particular set or attitude

TABLE XXVII

SUB-PROBLEMS IN INVESTIGATIONS
IN MOVEMENT PARALLAX

Investigator	Year	Geometry of Parallax	Distance Esti-mates	Threshold Determin-ations	Para-meter Effects	Experien-tial Effects	General Dis-cussion
Helmholtz (ref. 35)	1866						X
Bourdon (ref. 10)	1902						X
Tschermak (ref. 77)	1939			X			
Graham, et al. (ref. 32)	1948	X		X	X		
Zegers (ref. 85)	1948				X		
Rose (ref. 66)	1952				X		
Gibson, et al. (ref. 26)	1959					X	
Ogle (ref. 16)	1962	X					
Dees (ref. 17)	1966		X				

TABLE XXVIII

EQUIVALENCE OF SYMBOLS IN DIAGRAMS
FOR PARALLAX AND STEREOPSIS

Magnitude	Symbols used in Parallax Diagrams by Ogle (ref. 16, p.262)	Symbols used in Parallax Diagrams by Graham, et al.(ref. 32)	Symbols used in Stereopsis Diagram by Ogle (ref. 16, p.292)
Distance to Fixation point from eye	y_o	R_f	b_v
Distance of Object point from eye	y	$R_f + \delta$	$b_v + \Delta b_v$
Depth Interval	$y - y_o$	δ	Δb_v
Angle of Rotation of eye	ϕ	Θ_r	
Angle of Parallax or stereopsis	ρ	$\Delta\Theta$	η

NOTE: Subscripts in two right columns by the authors.

TABLE XXIX

PARALLAX RATIO THRESHOLDS ρ / ϕ

Experimental Conditions	Tschermak			Graham, et al.		
	Depth Interval	Object Distance	Parallax Ratio	Depth Interval	Object Distance	Parallax Ratio
	$(y-y_o)$	y	$\frac{y-y_o}{y}$	$y-y_o$	y	$\frac{y-y_o}{y}$
Horizontal Axis	0.8 mm	210 mm	$3.88(10^{-3})$	.008 to .031 in.	9.44 in. (24 cm)	$.85(10^{-3})$ to $3.28(10^{-3})$
Vertical Axis	5-9 mm	400 mm	$12.5(10^{-3})$ to $22.45(10^{-3})$	.011 to .065 in.	9.44 in. (24 cm)	$1.17(10^{-3})$ to $6.90(10^{-3})$
Source of Data	Table I Monocular, Head Oscillating (Ref. 76, p. 466)			(Ref. 32, p. 220)		

TABLE XXX

PARALLAX DIFFERENTIAL ANGULAR VELOCITY THRESHOLDS (ω_t)

Parameter	Level	Differential Angular Velocity		Extreme Limits (Rounded)
		Log ω_t	ω_t	
Luminance of background in millilamberts (ref. 32, p.213)	Log I / I 1.0 / 10 -2.3 / 0.005	1.55 ($\bar{M}$) 2.51 ($\bar{M}$)	35.50 sec. of arc per sec. 316.3 sec. of arc per sec.	316 sec. of arc per sec.
Rate of movement of object-points (head stationary) (ref. 32, p. 215)	.1279 rad. per sec. of arc .3183 rad. per sec. of arc	1.23 2.13	16.99 sec. of arc per sec. 134.9 sec. of arc per sec.	17 sec. of arc per sec.
Axis of Parallax Movement (ref. 32, p. 219)	0° Axis 240° Axis*	1.52 ($\bar{M}$) 1.81 ($\bar{M}$)	33.12 sec. of arc per sec. 64.57 sec. of arc per sec.	-

*240° axis selected since maximum value of ω_t associated with this axis, minimum with 0° axis.

TABLE XXXI

CHANGE IN PARALLAX THRESHOLDS WITH INCREASE IN MAGNITUDE OF INDEPENDENT VARIABLE

Type of Variable	Independent Variable	Investigator			
		Tschermak (ref.76)	Graham et al.(ref. 32)	Zegers (ref. 85)	Rose (ref. 66)
Visual Field Conditions	Angular size of field			0	
	Luminance of background in millilamberts (I)		-		
Movement Properties	Axis of movement Vertical axis rel. to horizontal	+	+		-
	Rate of relative movement		+	+	
Stimulus - Target Conditions	Differential size of 2 objects		0		
	Offset			C	

LEGEND:
+ means increase in threshold
- means decrease in threshold
0 means little or no change in threshold
C means an effect dependent on a complex pattern of factors

TABLE XXXII

LINEAR DEPTH INTERVALS CALCULATED FOR DIFFERENT DISPARITY ANGLES AND REPRESENTATIVE FIXATION DISTANCES

Ogle (ref. 16, p. 293)

η = 12 seconds of arc									
Δb	Fixation distance b								
	25 cm.	40 cm.	75 cm.	1 m.	4 m.	10 m.	25 m.	40 m.	1,110 m.
Distal	0.05 mm	0.14 mm	0.51 mm	0.9 mm	14 mm	9.1 cm	58 cm	150 cm	∞
Proximal	0.05 mm	0.14 mm	0.51 mm	0.9 mm	15 mm	8.9 cm	55 cm	139 cm	555 m

η = 20 seconds of arc									
Δb	Fixation distance b								
	25 cm.	40 cm.	75 cm.	1 m.	4 m.	10 m.	25 m.	40 m.	667 m.
Distal	0.09 mm	0.24 mm	0.85 mm	1.5 mm	24 mm	15 cm	94 cm	241 cm	∞
Proximal	-0.09 mm	-0.24 mm	0.85 mm	1.5 mm	24 mm	14.8 cm	90 cm	226 cm	333 m

TABLE XXXIII

STEREOPTIC THRESHOLDS: MAGNITUDE OF η_t

Investigator	Year	Ref.	Range of Stereopsis Threshold Angle in Sec. of Arc	Distance (Range)	Apparatus Type	Time of Exposure	N (No. of Ss)
Stratton	1898	71	24 Sec. of Arc	580 Meters	Pseudoscope		1
Howard	1919	42	Best Ss: 1.8-2.7 Sec. of Arc (n = 14) Worst Ss: 10.6-136.2 Sec. of Arc (n = 24)	6 Meters	2 Rods (Vert. rods, Diam. 1 cm., Aperture = 20 x 12 cm. Threshold at 75% probability		106
Woodburne	1934	80	2.12 Sec. of Arc (Average of near and far	2 Meters	2 Illum. Slits Method: Constant Stimulus Target Vis. Angle Constant	1.5 Sec. of time	7
Ten Doelschate	1955	74	4.68 Sec. of Arc mean error	50 Meters	3 Rod Apparatus		100

TABLE XXXIV

STIMULUS-PARAMETERS EFFECTING STEREOPTIC THRESHOLD (η_t)

Classification of Parameter							
System Status	Dimensional Status		Specific Parameter	Investigator	Year	Ref. No.	Direction of Change of With Parameter Increase
Input Properties (Target)	L	of object	Length of Objects	Anderson, et al.	1923	2	Decrease
				Matsubayashii	1938	30	
			Thickness of Objects	Matsubayashii	1938	30	
			Shape of Objects	Langlands	1926	49	
		of space	Lateral Separation of Objects	Matsubayashii	1937	30	Increase
				Graham, Riggs, Mueller & Solomon	1949	31	Increase
			Viewing Distance	Matsubayashii	1938	30	Decrease
				Teichner, et al	1955	75	
	t		Duration of Exposure	Langlands	1926	49	Conflicting Results
				Ogle & Weil	1958	59	
	I		Luminance or Illum. of Target	Mueller & Lloyd	1948	36	Decrease
				Ludvigh	1947	53	Decrease
				Berry, Riggs & Duncan	1950	8	Decrease

TABLE XXXV

RECEPTOR-PARAMETERS EFFECTING STEREOPTIC THRESHOLD (η_t)

Receptor Conditions					
	Specific Parameter	Investigator	Year	Ref. No.	Change of Stereoptic Threshold Angle With Parameter Increase
Sensitivity Properties	Visual acuity	Frey	1953	23	Tends to decrease with increase in visual acuity. Some conflicting evidence.
	Relative visual acuity of 2 eyes	Matsubayashii	1938	30	Constant except at very low acuity for 1 eye
	Dark adaptation	Mueller & Lloyd Lit	1948 1959	56 52	Decreases with increase in dark adaptation, i.e., with increase in retinal sensitivity.
Angular Properties	Axis of Disparity	Helmholtz Ogle	1925 1958	35 16	Horizontal disparity the dominant factor. Some effects of vertical disparity in pathological cases.
	Peripheral angle of excitation	Ellerbrock Fabre & Lapouille Burian	1949 1950 1951	20 21 11	Threshold increases toward periphery
	Angular Width of Field	Langlands	1926	49	For 8° field, greater than for 1° field
	Angle of convergence	Wright Rady & Ishak Ogle	1951 1955 1956	83 65 16	Conflicting results

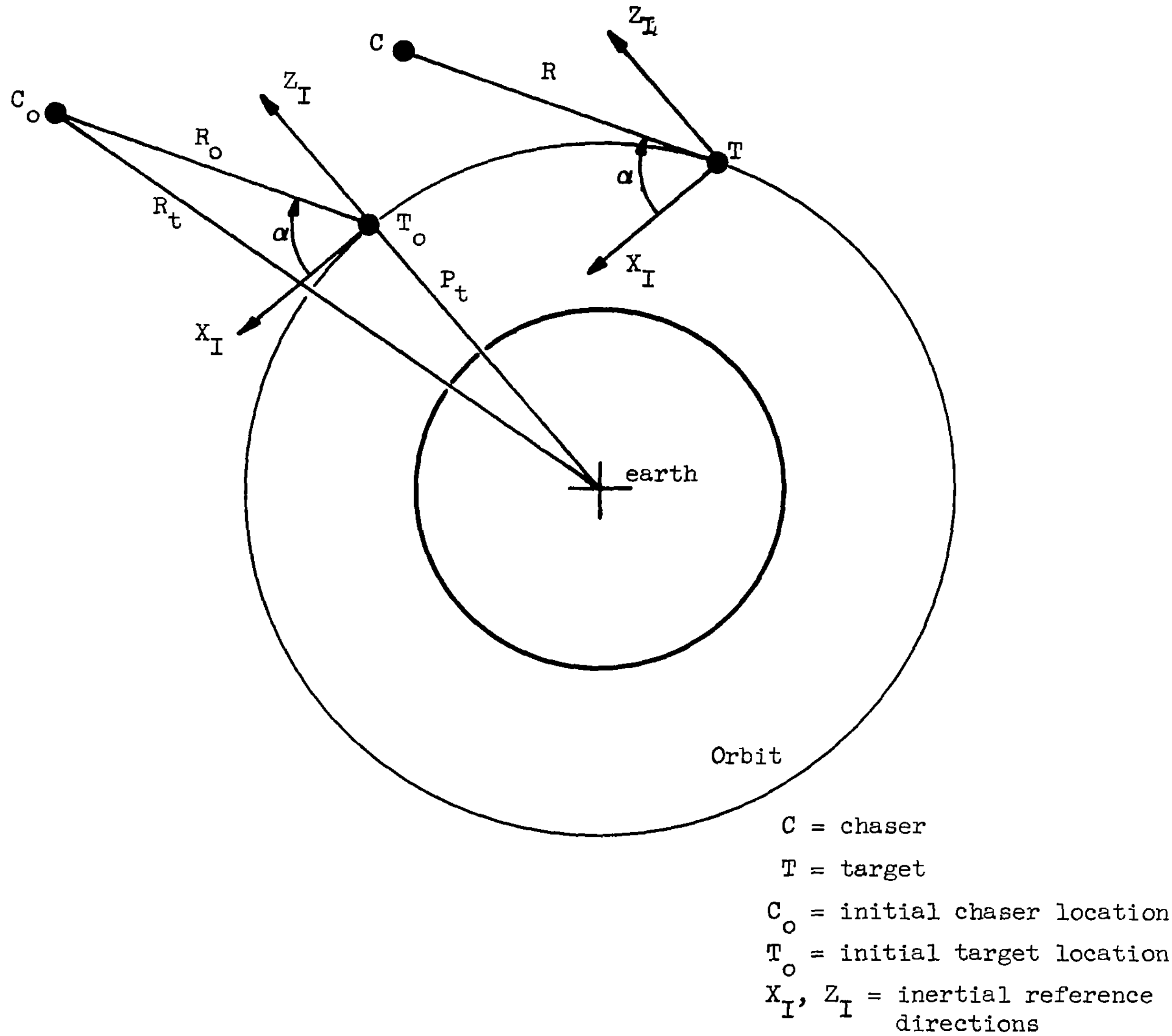


Fig. 1 Pitch Plane Geometry for Guidance Scheme #1: Inertial Line-of-Sight Collision Course

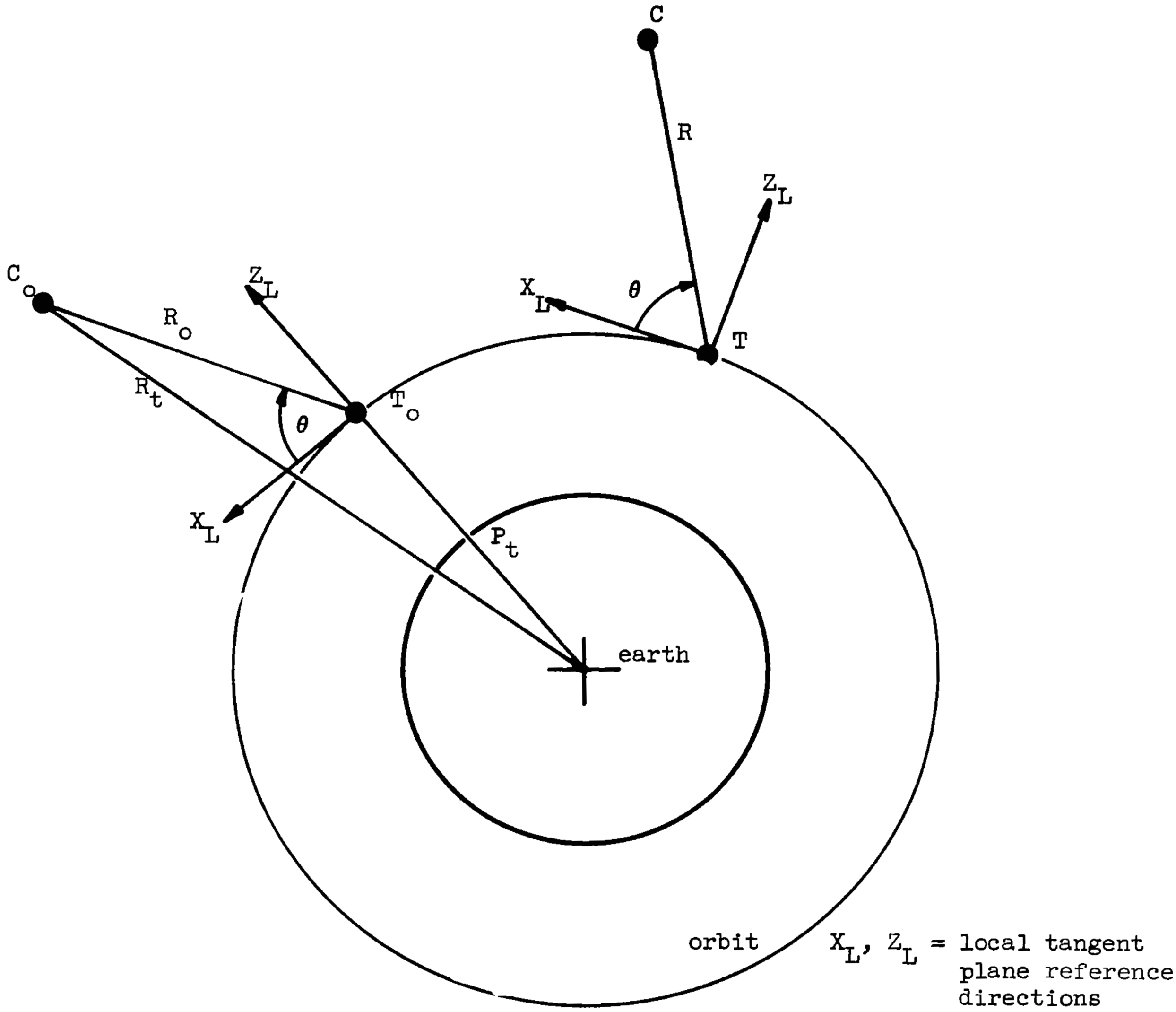


Fig. 2 Pitch Plane Geometry for Guidance Scheme #2: Rotating Line-of-Sight Collision Course

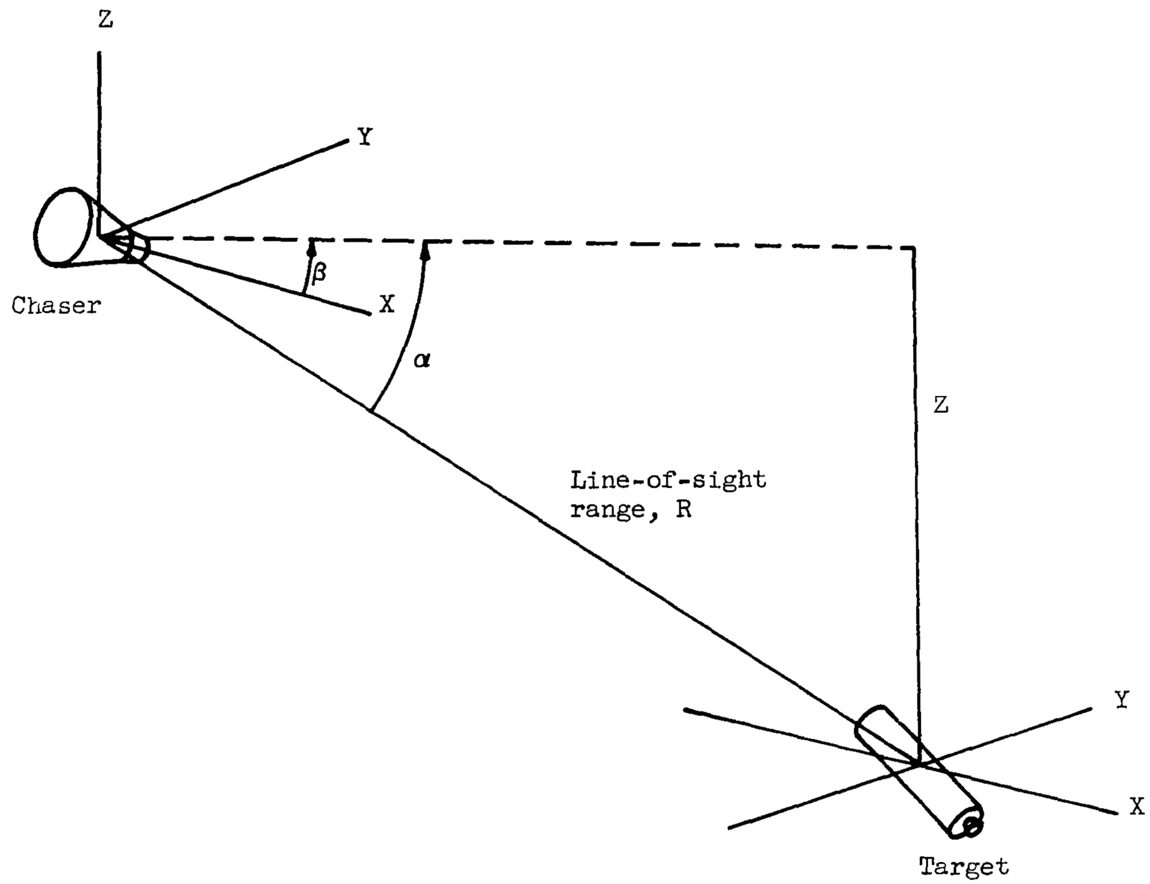


Fig. 3 Line-of-Sight Relations Between Commanded Module and Spacecraft

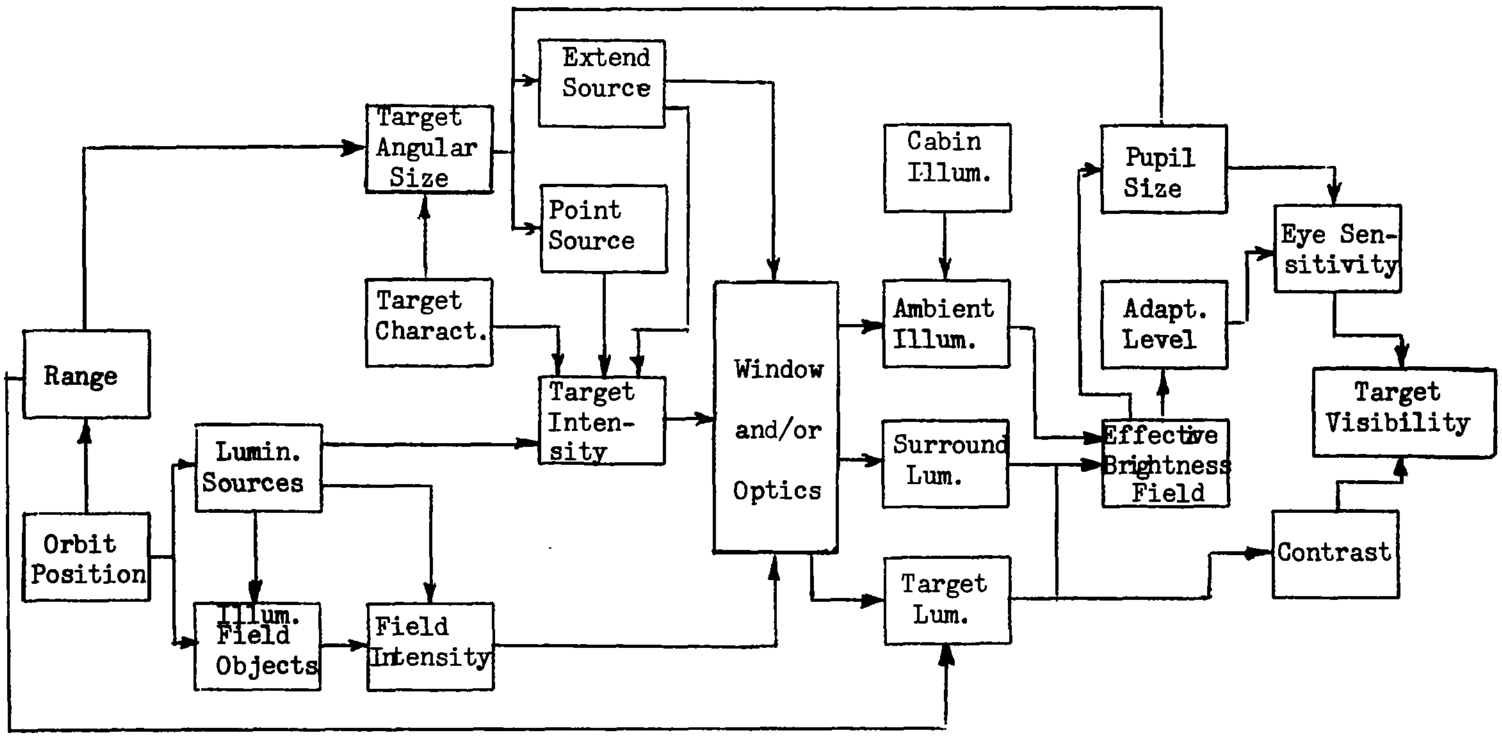
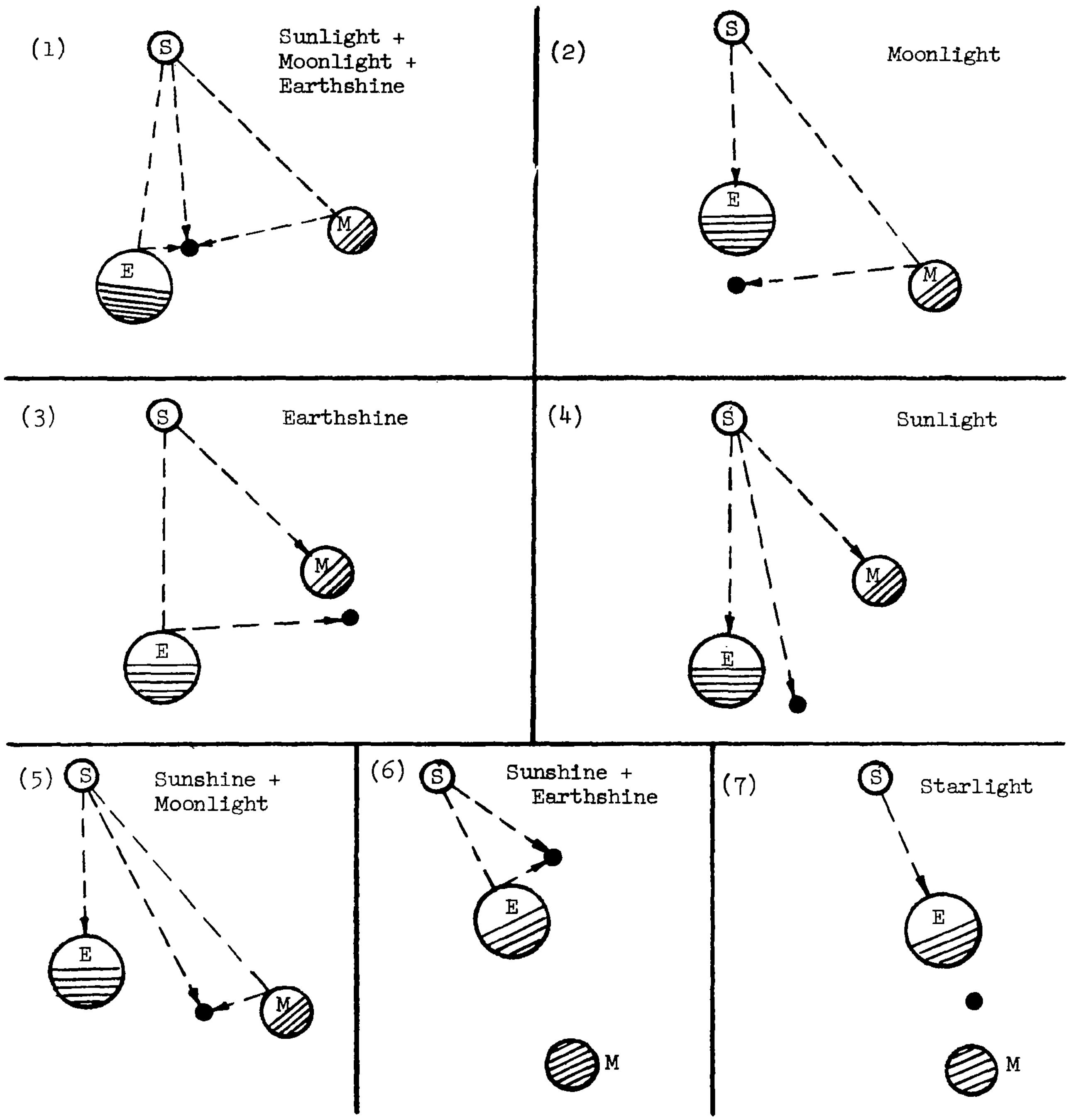


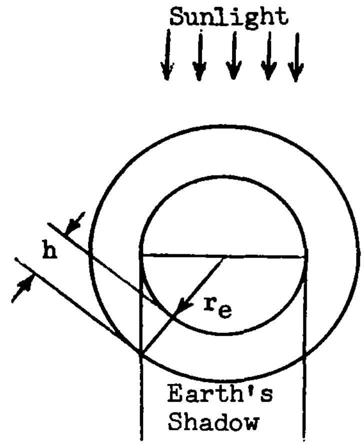
FIGURE 4 PHYSICAL ENVIRONMENT PARAMETERS AND THEIR RELATIONSHIPS



NOTE: (1) Black dot is a spacecraft.
(2) The star field exists in all environments.

Fig. 5 Typical Spacecraft Illumination Environment as a Function of Mission and/or its Orbit Position

FIGURE 6 - MAXIMUM LINE OF SIGHT DISTANCE AND TIME IN DARK FOR EARTH ORBITING SPACECRAFT



(a) Ratio of Approximate Time in Dark to Orbit Period.

Assumptions:

1. Spherical Earth.
2. Circular Orbits (Equatorial).
3. 32' Decollimation of Sunlight Negligible.

$$\frac{t_d}{P_o} \cong \frac{1}{2} - \left[\frac{\cos^{-1}\left(\frac{r_e}{r_e + h}\right)}{180^\circ}\right]$$

Where: t_d = Time in dark (minutes)

P_o = Orbit period (minutes)

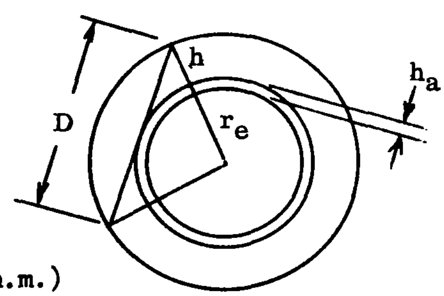
r_e = Earth radius (3440 n.m.)

h = Orbit altitude (n.m.)

(b) Maximum Line of Sight Distance Between Two Orbiting Spacecraft.

Assumptions:

1. Sperical Earth.
2. Circular Orbits (Equatorial).
3. 20 n.m. Altitude Earth "Aura".
4. Spacecraft and Target in Same Orbit.



$$D \cong 2\left[2\, r_e \left(h-h_a\right) + \left(h^2 - {h_a}^2\right)\right]^{\frac{1}{2}}$$

Where: D = Maximum line of sight distance (n.m.)

r_e = Earth radius (3440 n.m.)

h = Orbit altitude (n.m.)

h_a = Aura altitude (n.m.)

FIGURE 7 - STAR DENSITY VS. MAGNITUDE FOR THREE SIZES OF FIELD OF VIEW
[From ref. 24]

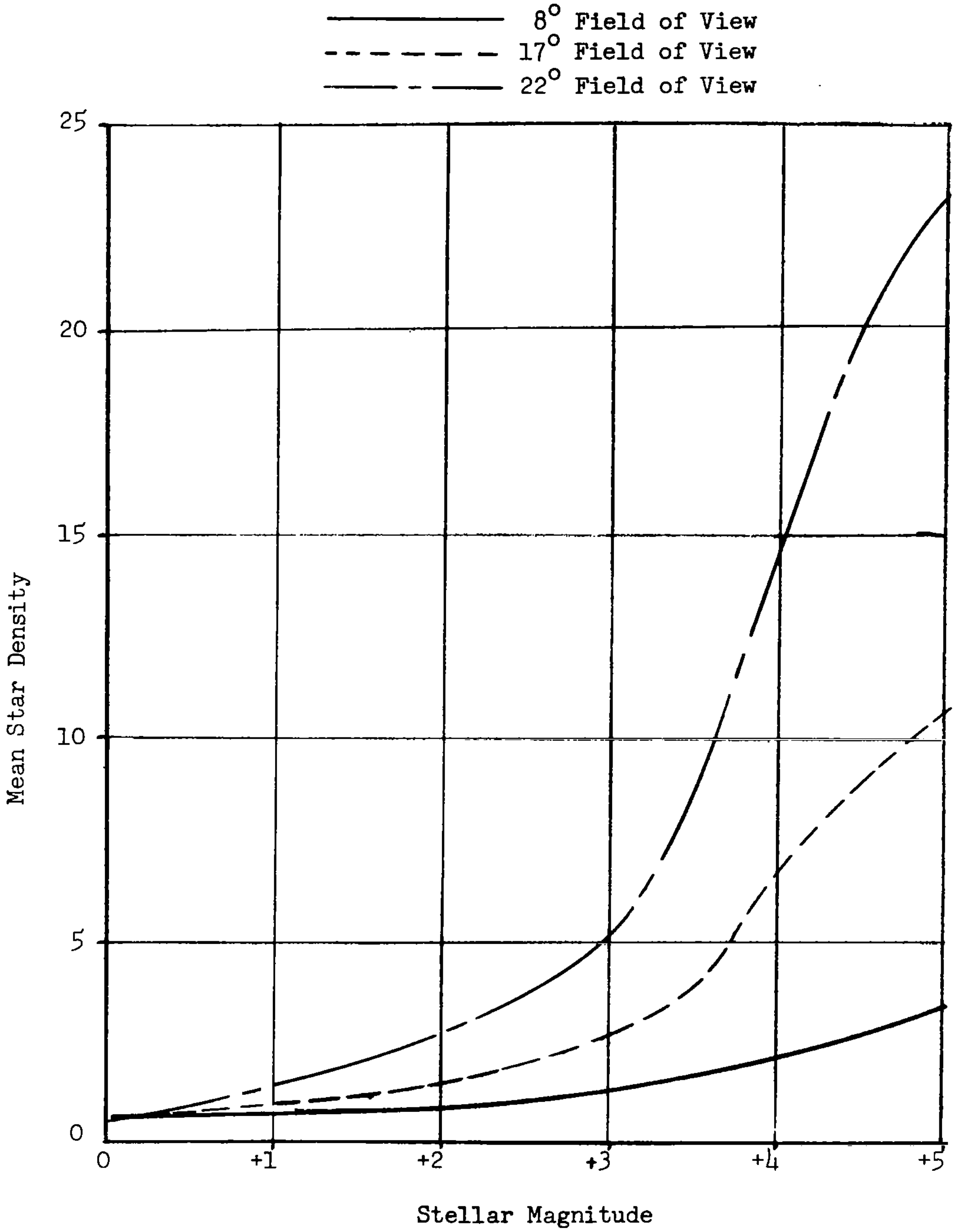


FIGURE 3 - MINIMUM VISUAL ACUITY AS A FUNCTION OF CONTRAST RATIO AND BACKGROUND LUMINANCE (REF. 2)

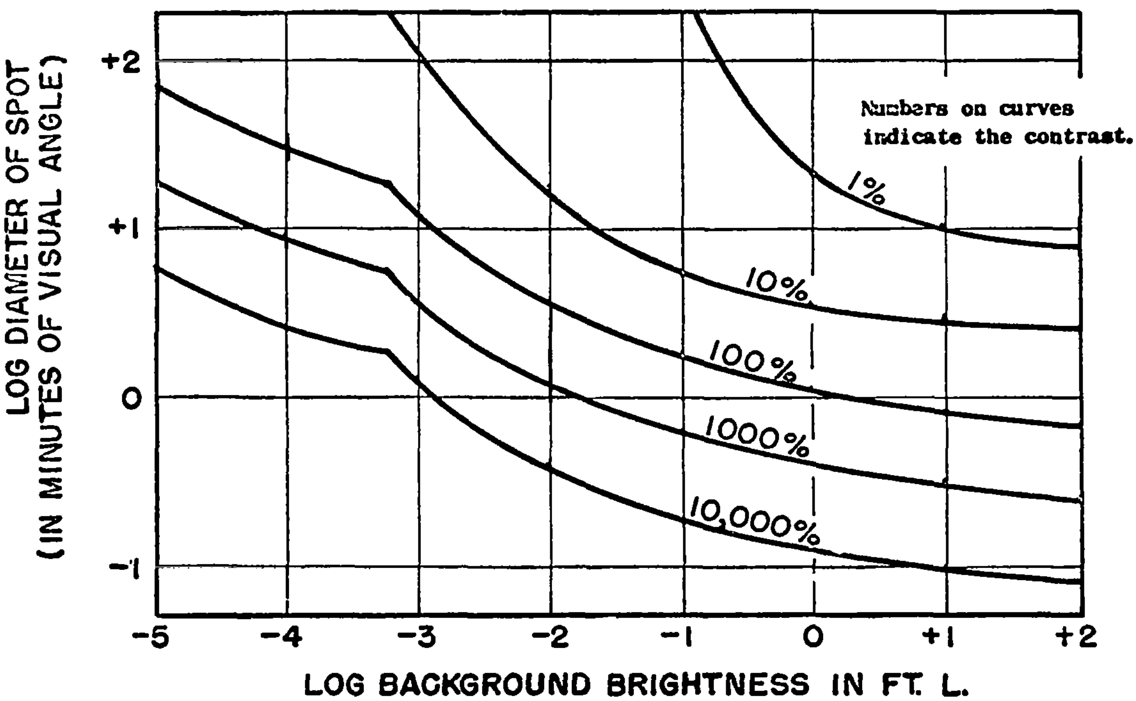


FIGURE 9: SURFACE BRIGHTNESS OF SPACECRAFT CORONA AS A FUNCTION OF MASS EJECTION RATE (REF. 12)

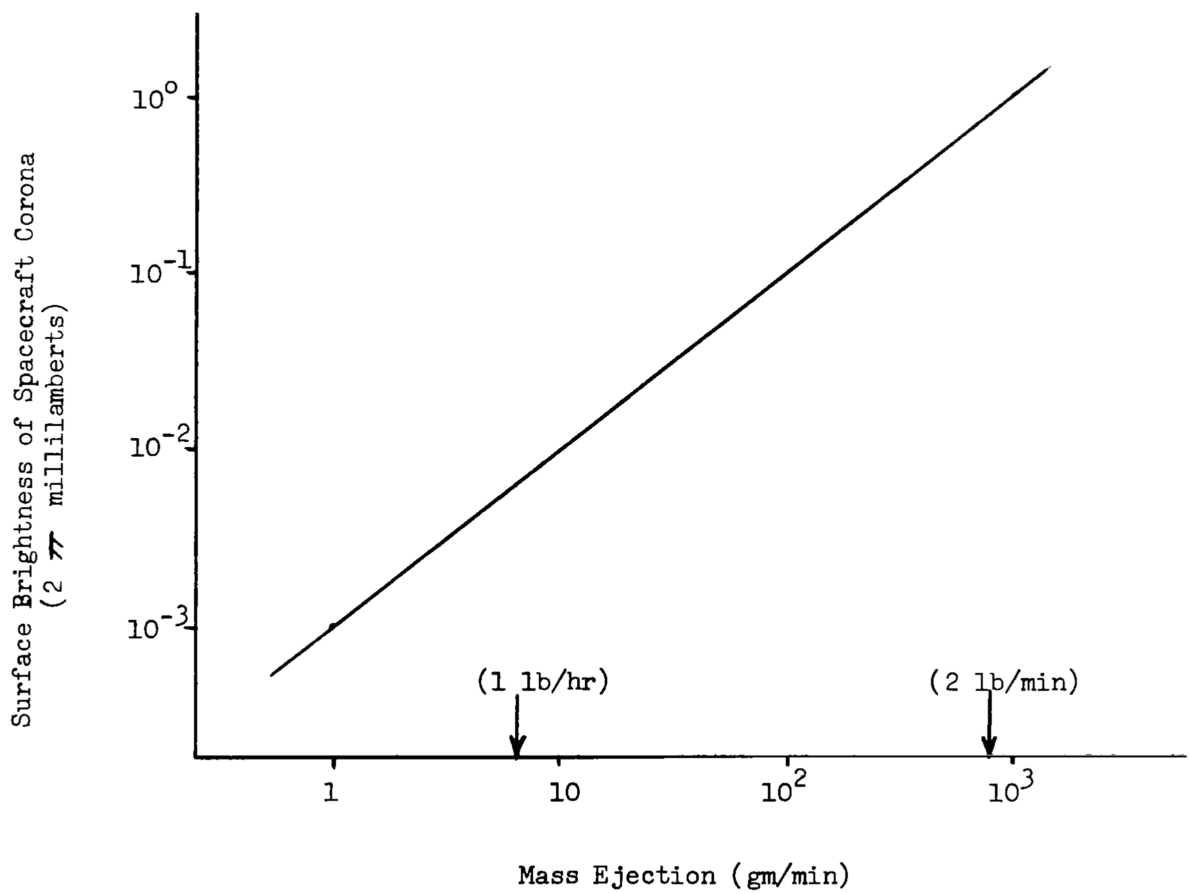
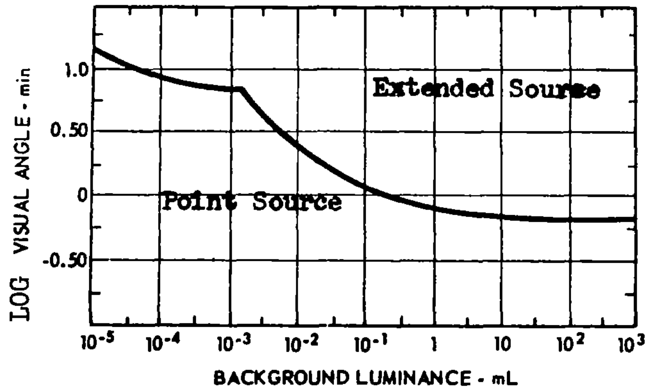


FIGURE 10: CRITICAL VISUAL ANGLE FOR POINT SOURCES AS A FUNCTION OF BACKGROUND LUMINANCE (REF. 2)



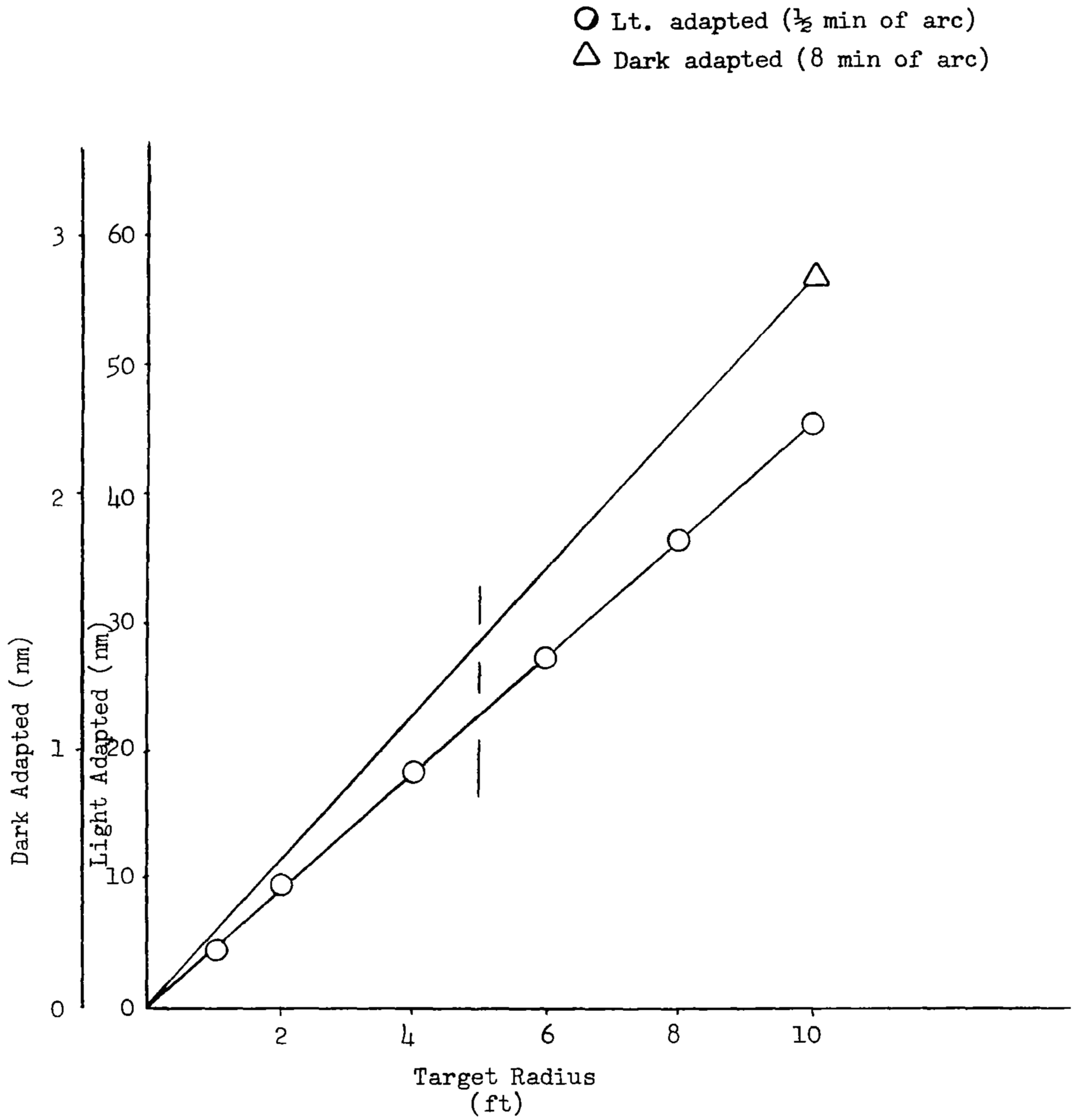


FIGURE 11: DISTANCE BEYOND WHICH A TARGET IS A POINT SOURCE

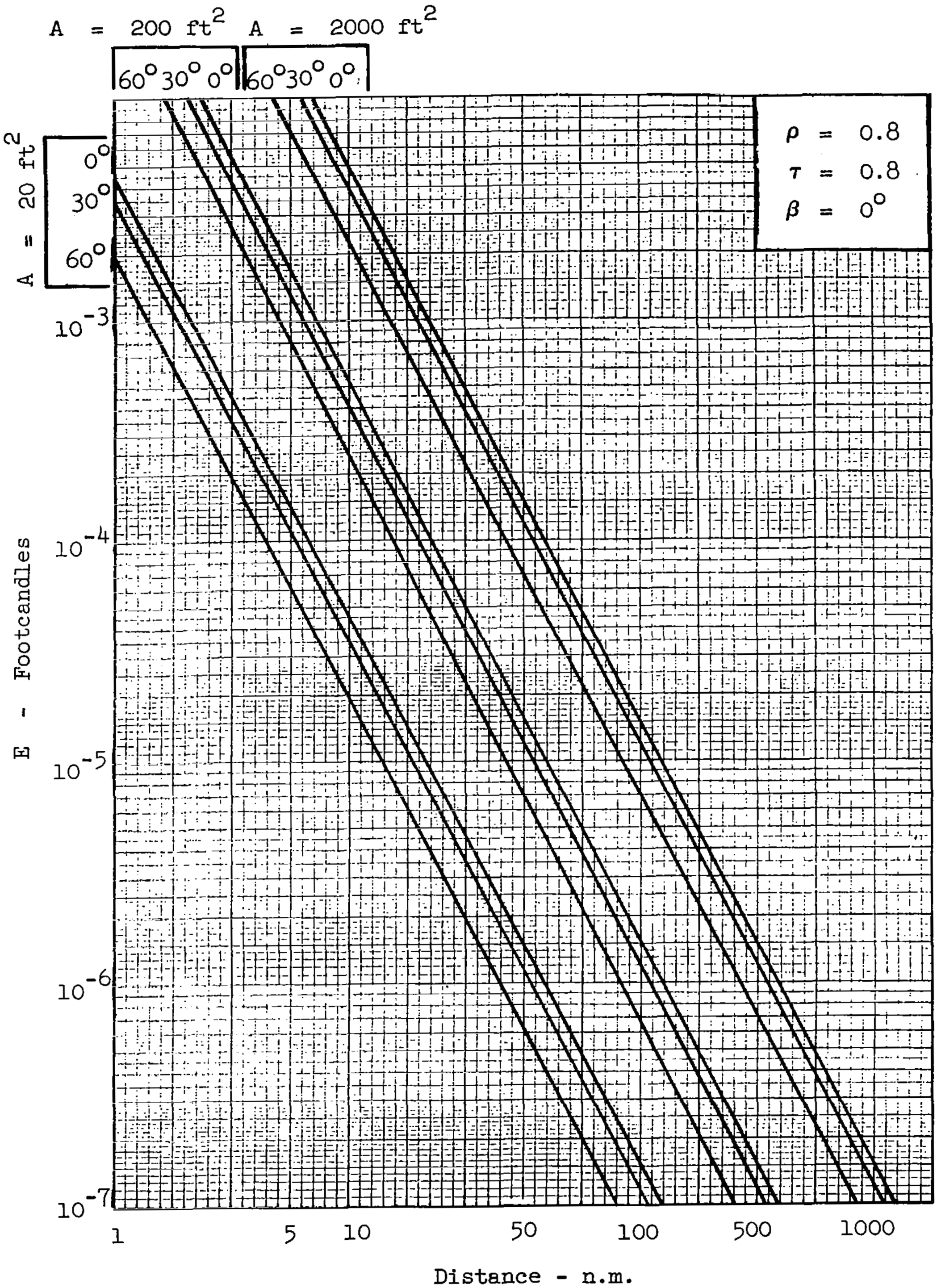


Figure 12. Illumination at the Eye Versus Range for a Sunlit Diffuse Flat Plate or Disc of Area (A)

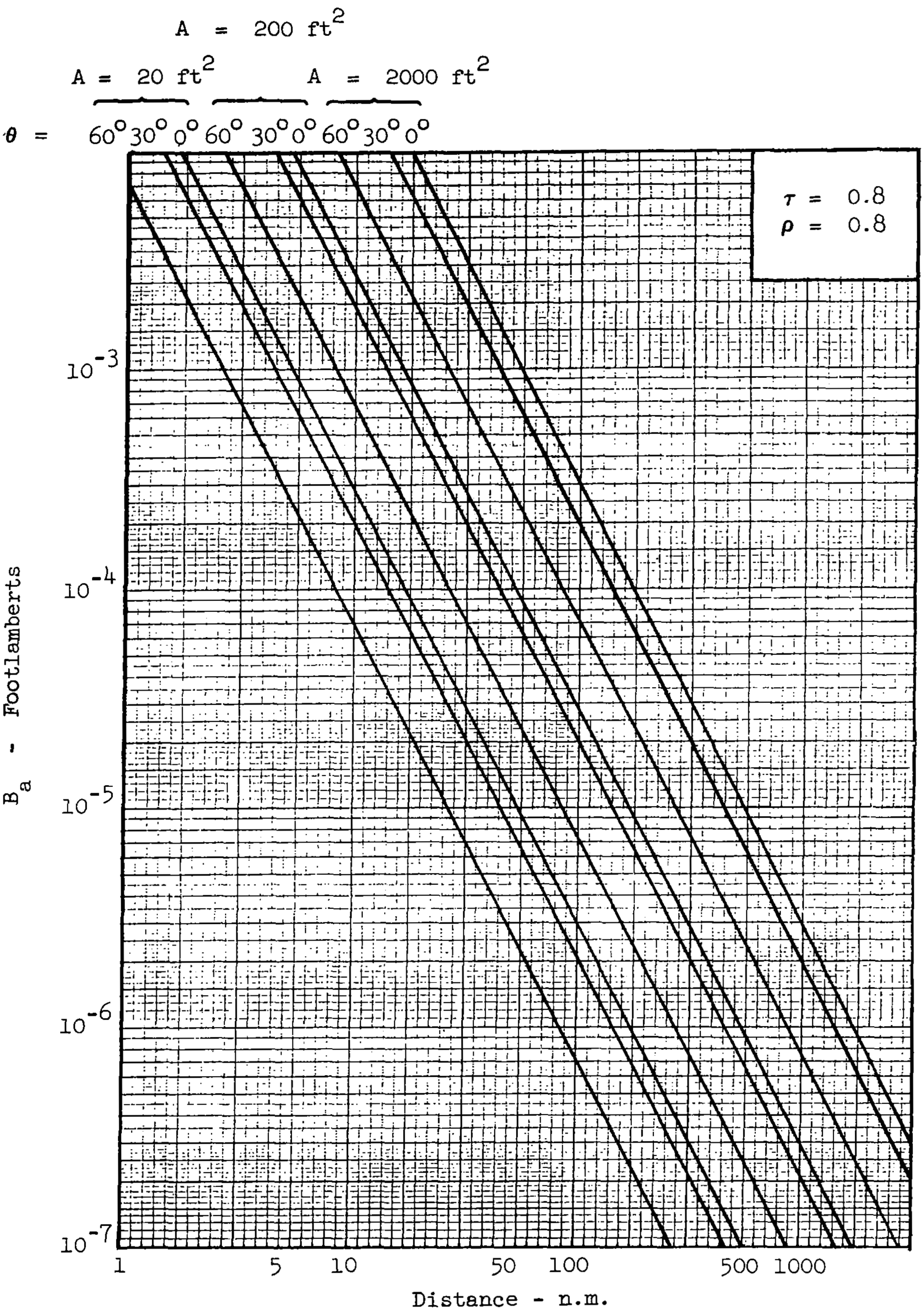


Figure 13. Target Brightness Versus Range for a Sunlit Diffuse Flat Plate or Disc of Area (A)

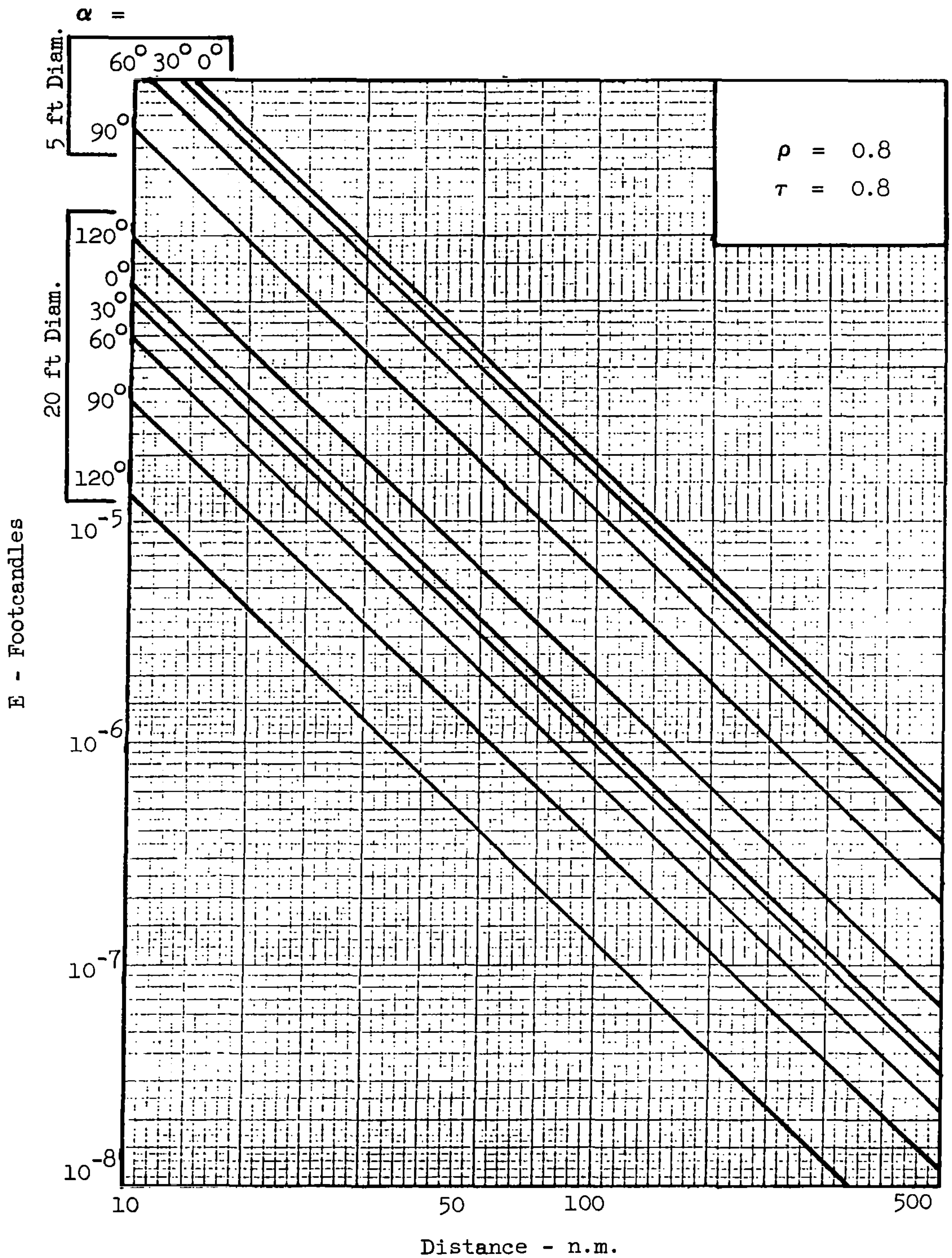


Figure 14. Illumination at the Eye Versus Range for a Sunlit Diffuse Sphere

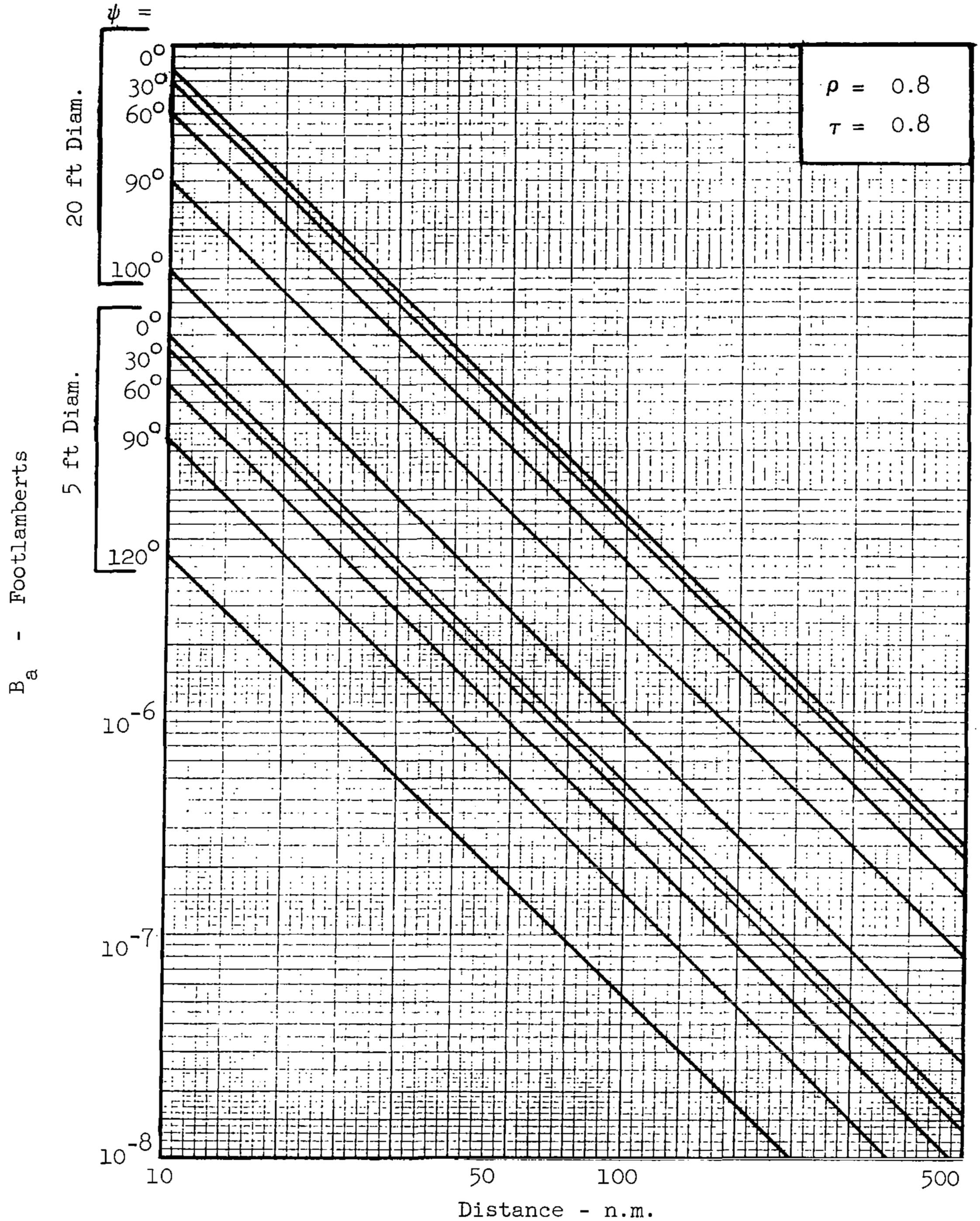


Figure 15. Target Brightness Versus Range for a Sunlit Diffuse Sphere

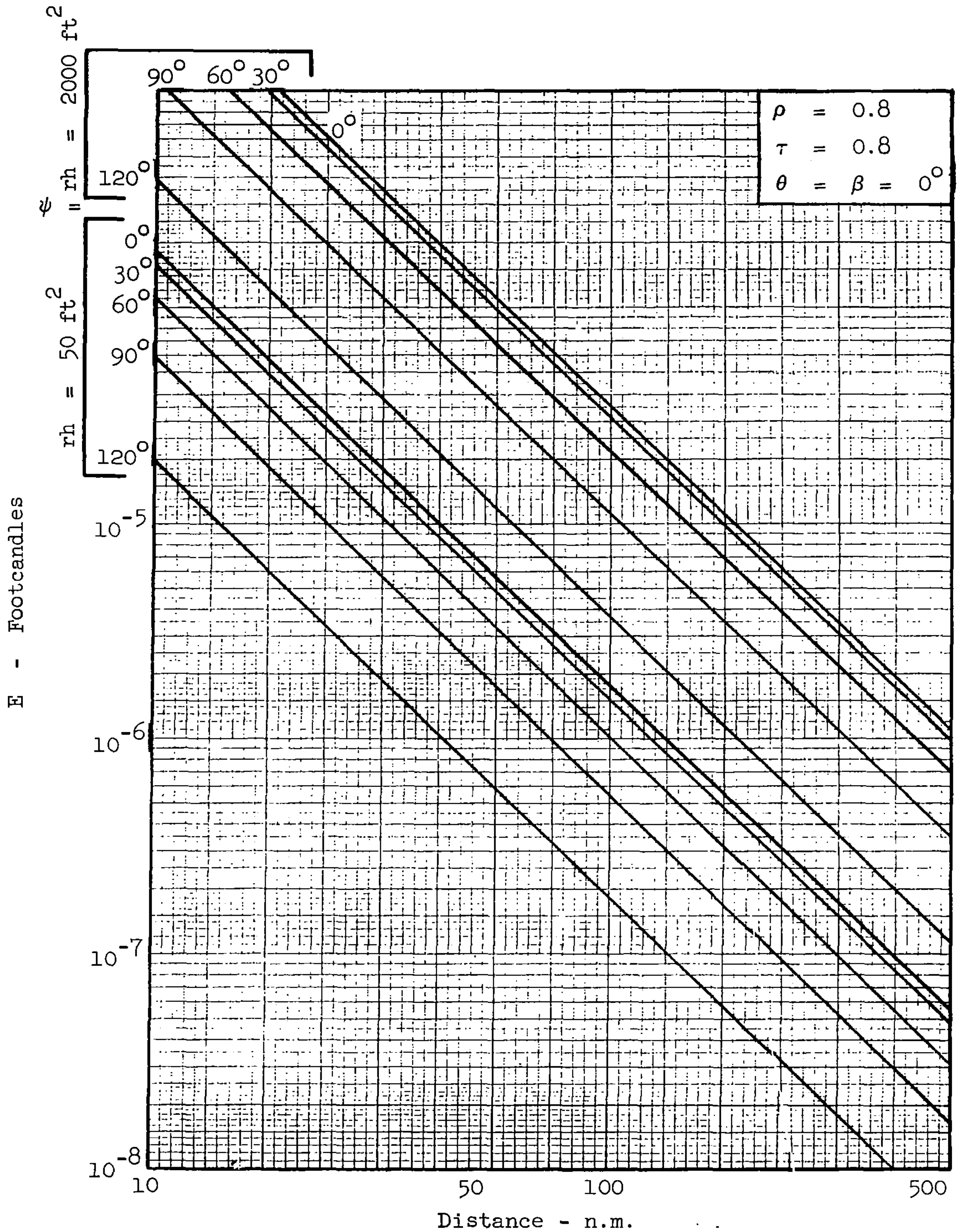


Figure 16. Illumination at the Eye Versus Range for a Sunlit Diffuse Cylinder of Radius (r) and Length (h)

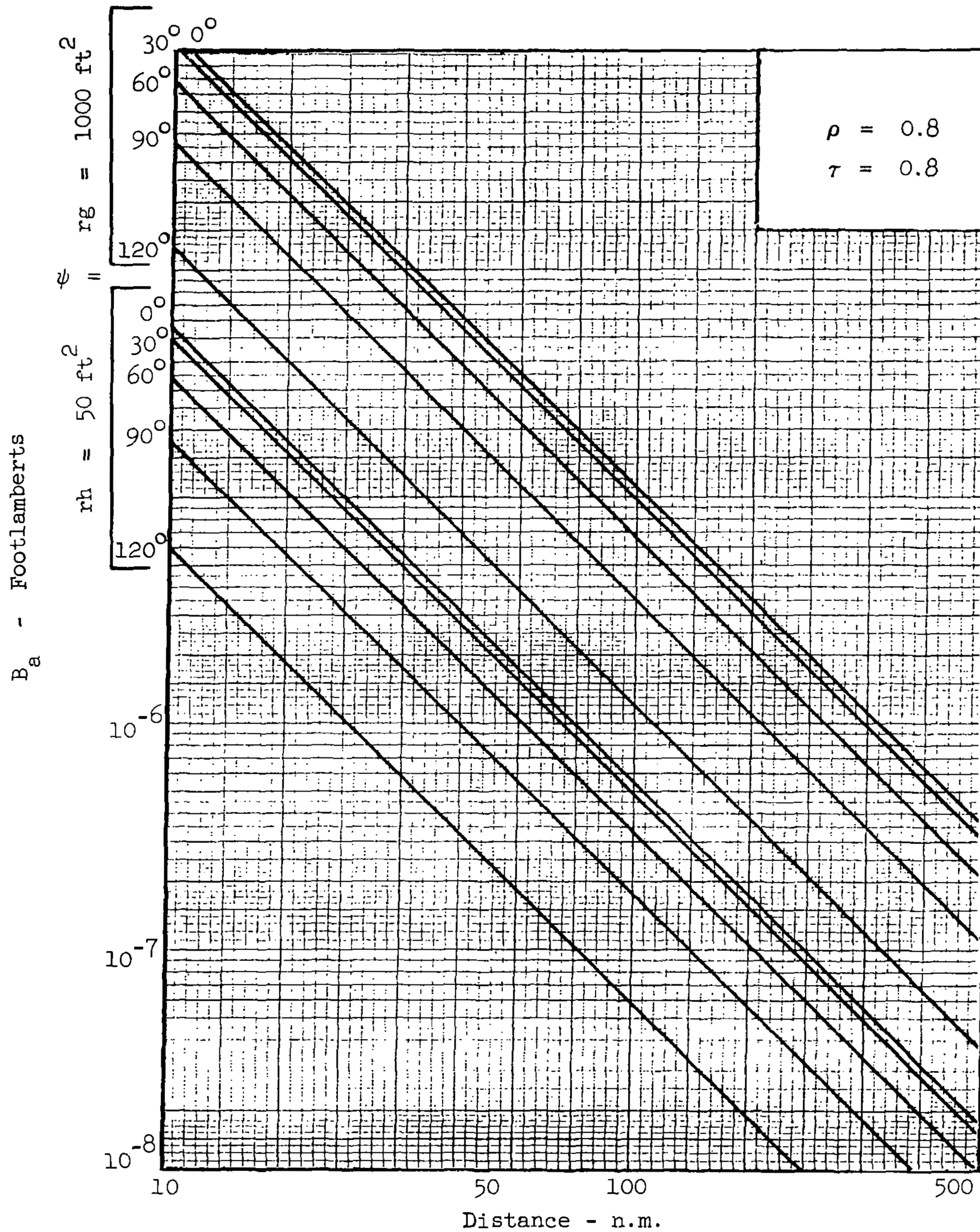


Figure 17. Target Brightness Versus Range for a Sunlit Diffuse Cylinder of Radius (r) and Length (h)

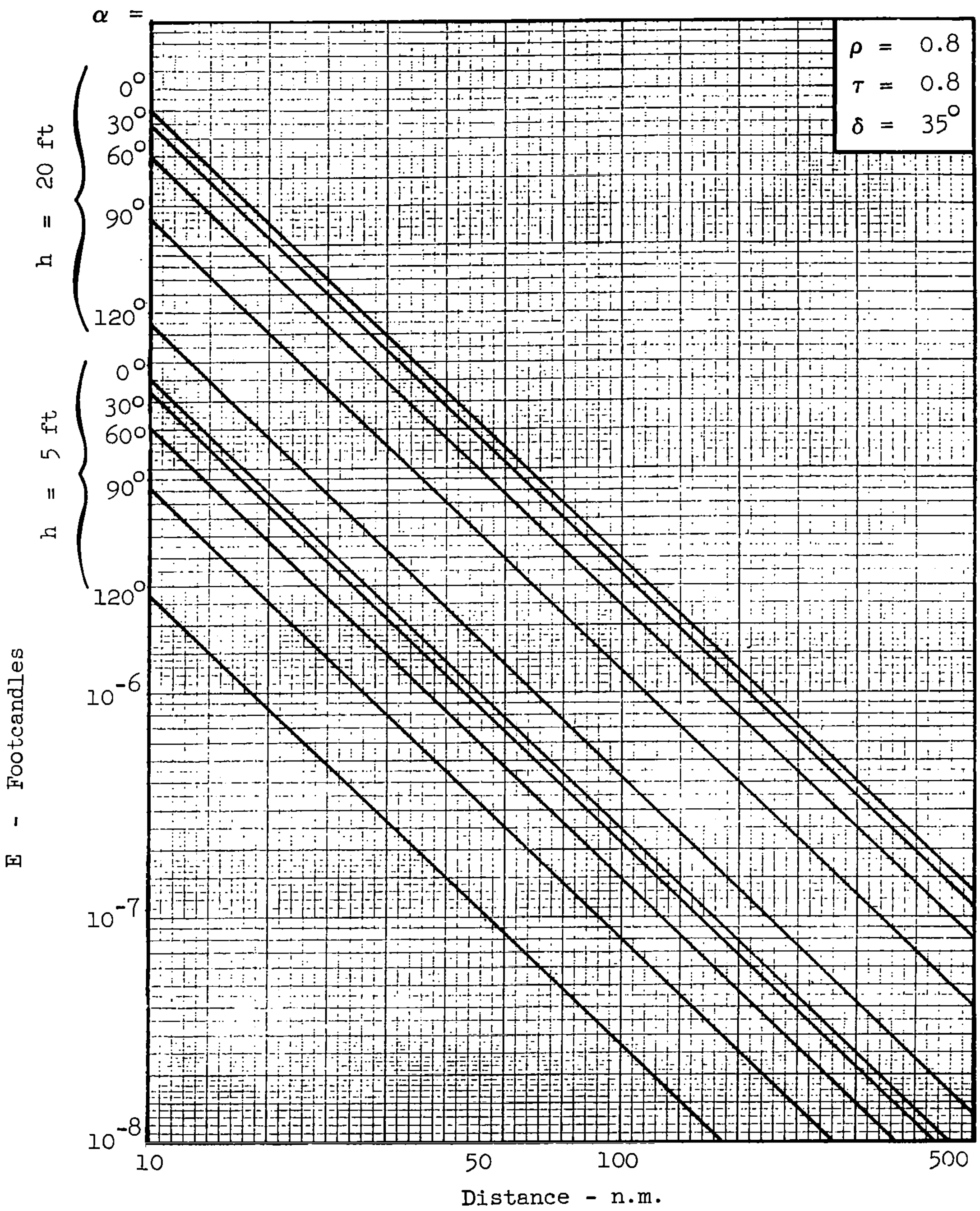


Figure 18. Illumination at the Eye Versus Range for a Sunlit Diffuse Cone of Height (h) and Cone Half Angle (δ)

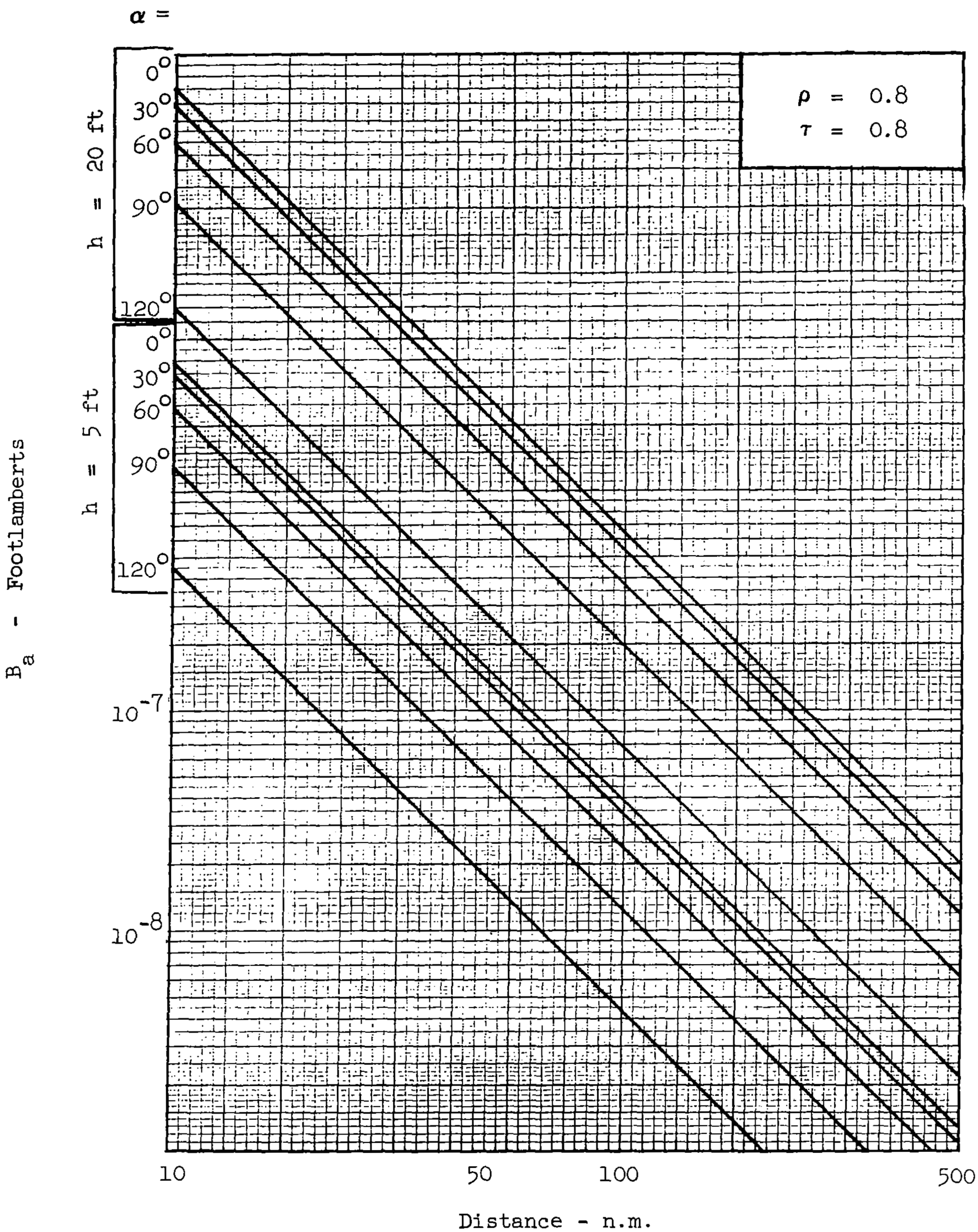
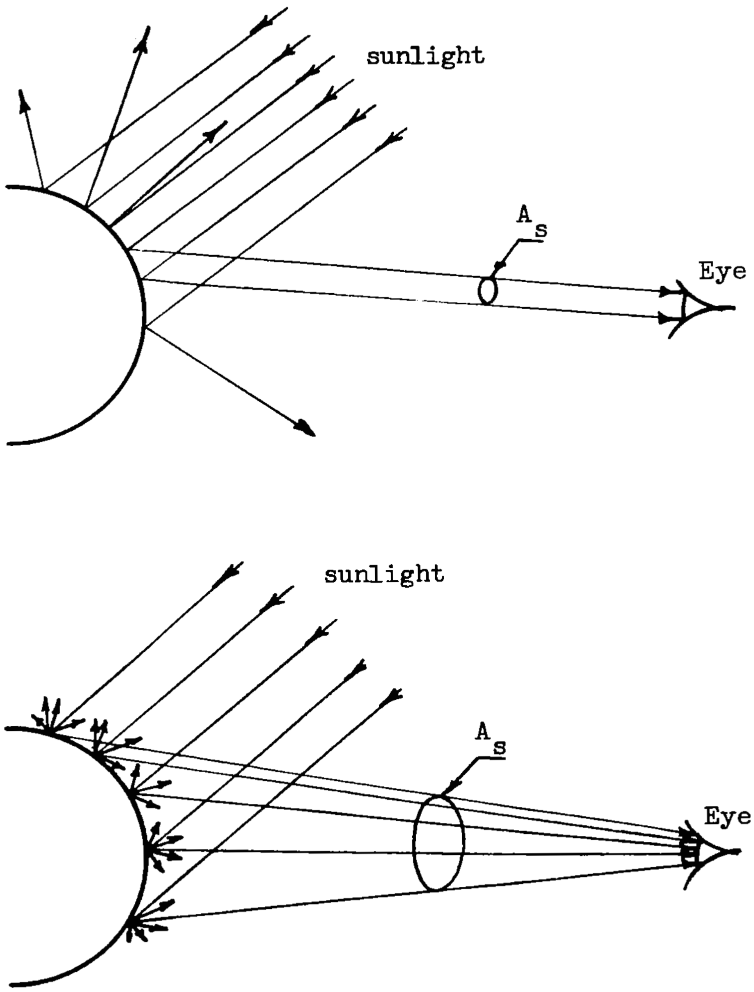


Figure 19. Target Brightness Versus Range for a Sunlit Diffuse Cone of Height (h) and Cone Half Angle (δ)

FIGURE 20 REFLECTION OF COLLIMATED LIGHT BY A SPECULAR AND A DIFFUSE SPHERE

Specular

Diffuse



A_s = solid angle subtended by light which enters the pupil of the eye

FIGURE 21: RELATIVE VISIBILITY VERSUS WAVELENGTH FOR THE LIGHT ADAPTED EYE (REF. 9)

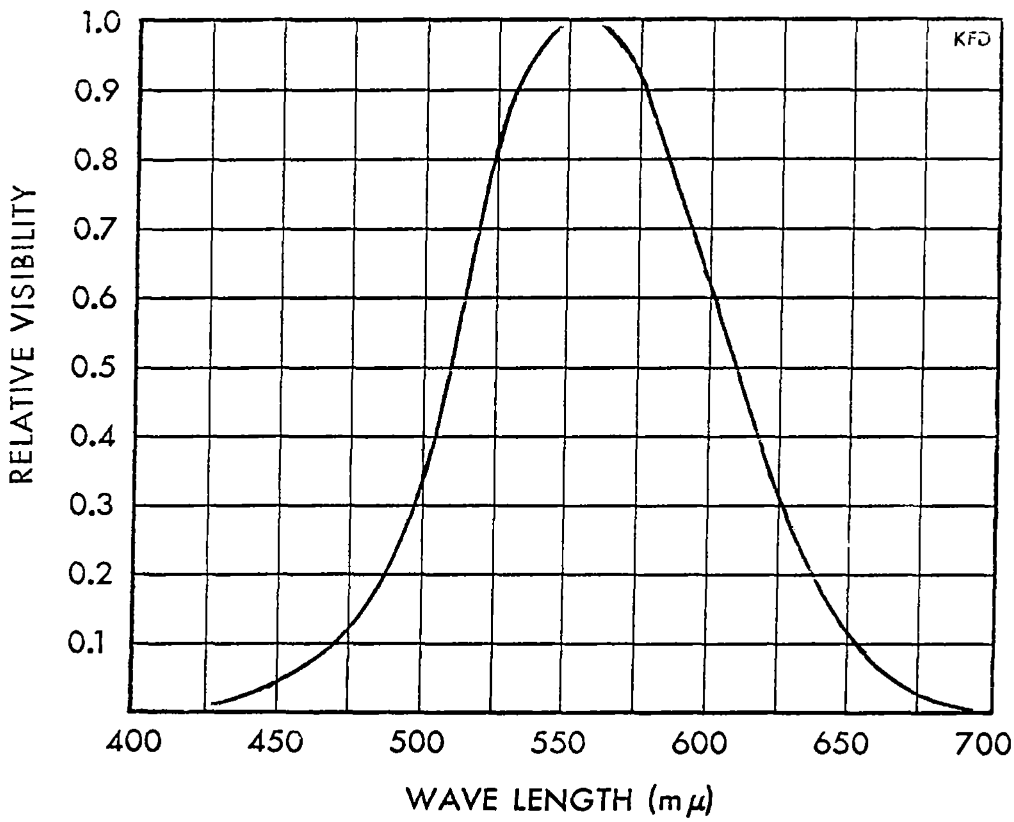


FIGURE 22: INTENSITY VARIATION AS A FUNCTION OF VIEWING ANGLE FOR A TYPICAL XENON FLASH LAMP (REF. 19)

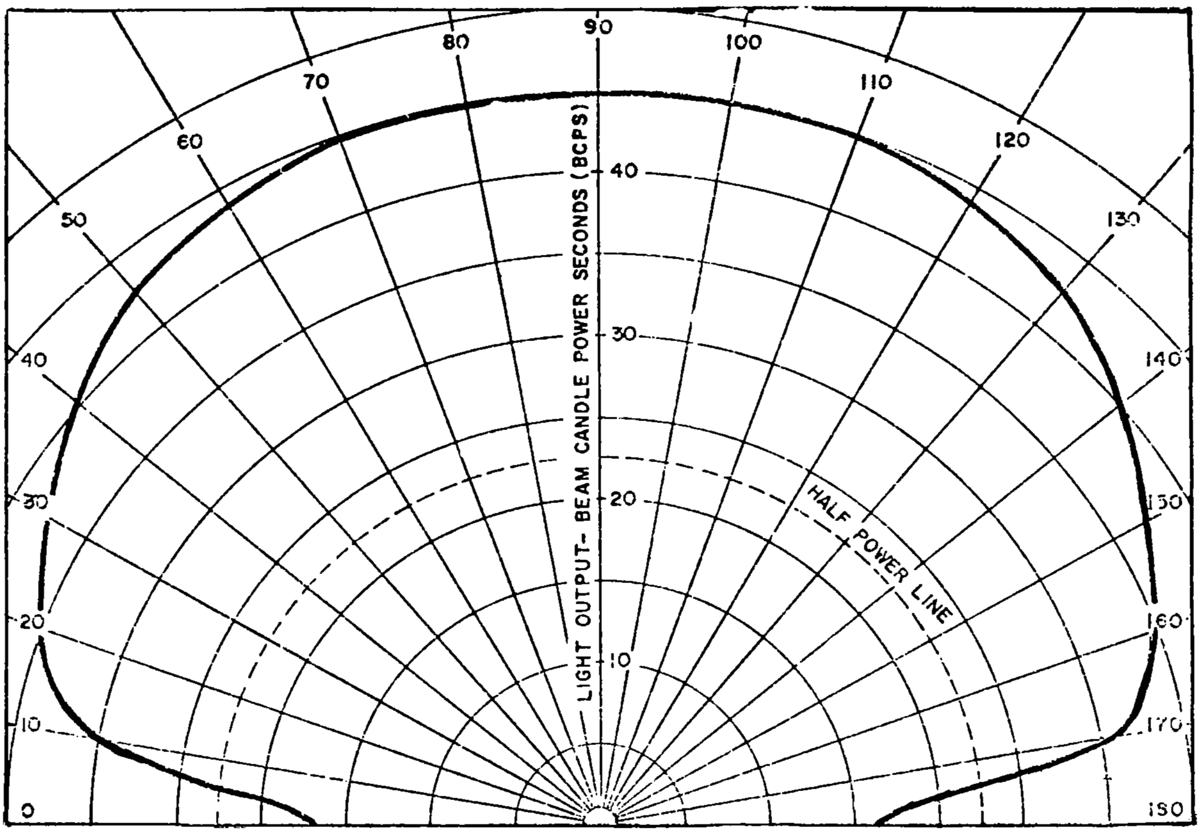
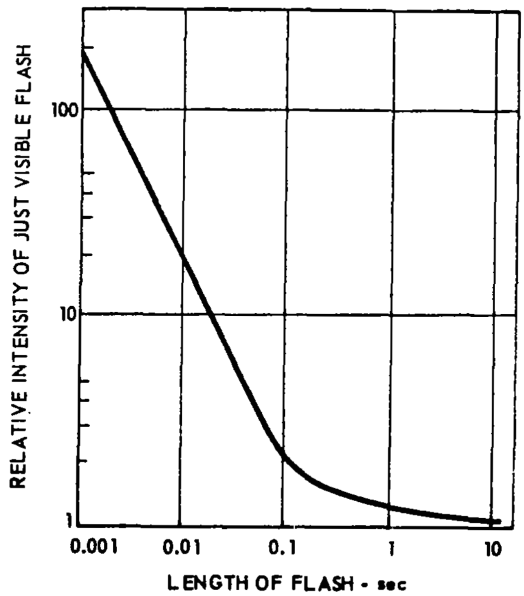
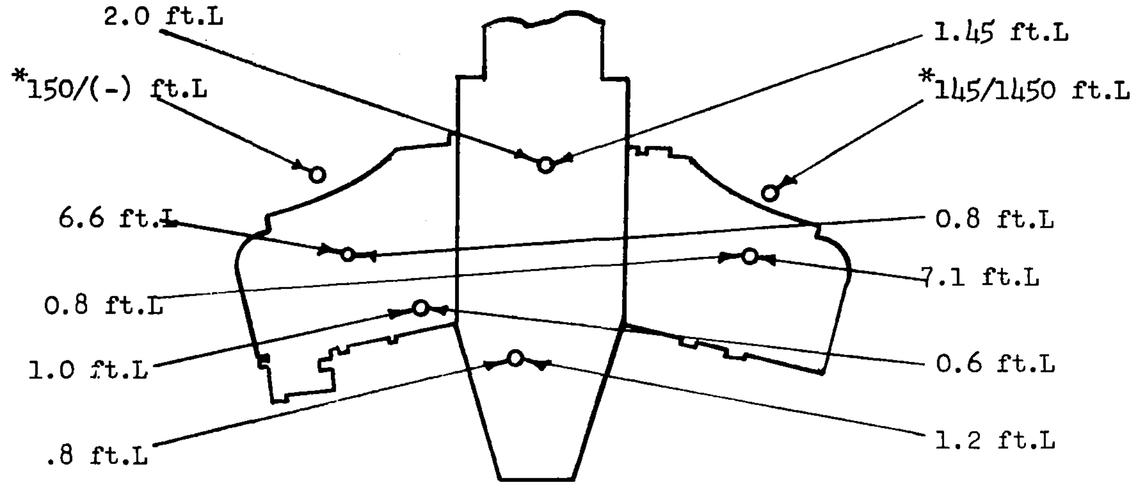


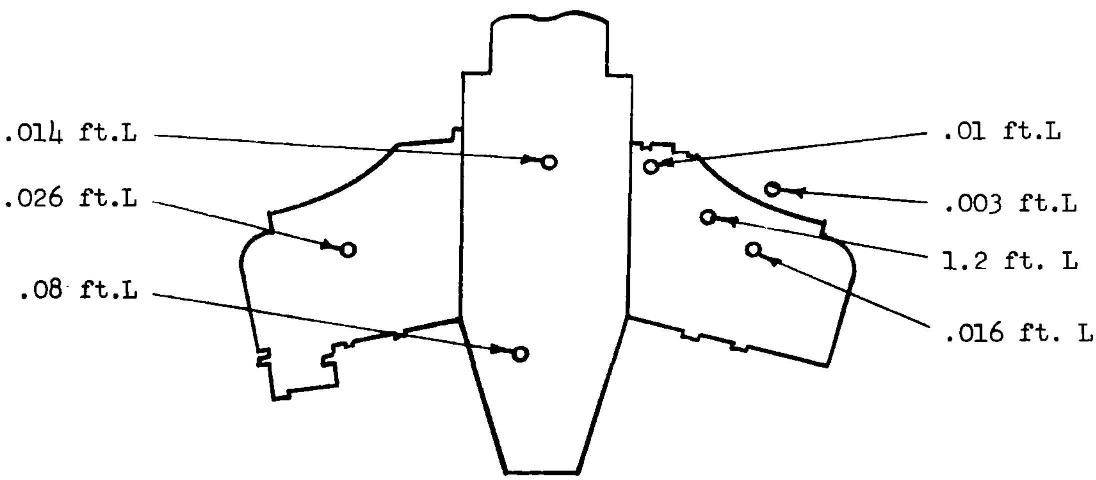
FIGURE 23: RELATIVE INTENSITY OF A JUST VISIBLE FLASH AS A FUNCTION OF FLASH DURATION (REF. 5)



a. Gemini V - internal spacecraft luminance levels (inflight measurements, daylight side, cabin lights on).



b. Gemini VI - Internal spacecraft luminance levels (postflight simulation, cabin lights dimmed).



* Black sky/earthshine (out of window)
(-) no reading

Figure 24 - Spacecraft Internal Illumination

FIGURE 25: THRESHOLD ILLUMINATION FROM A FIXED ACHROMATIC POINT SOURCE AS A FUNCTION OF BACKGROUND LUMINANCE (REF 7)

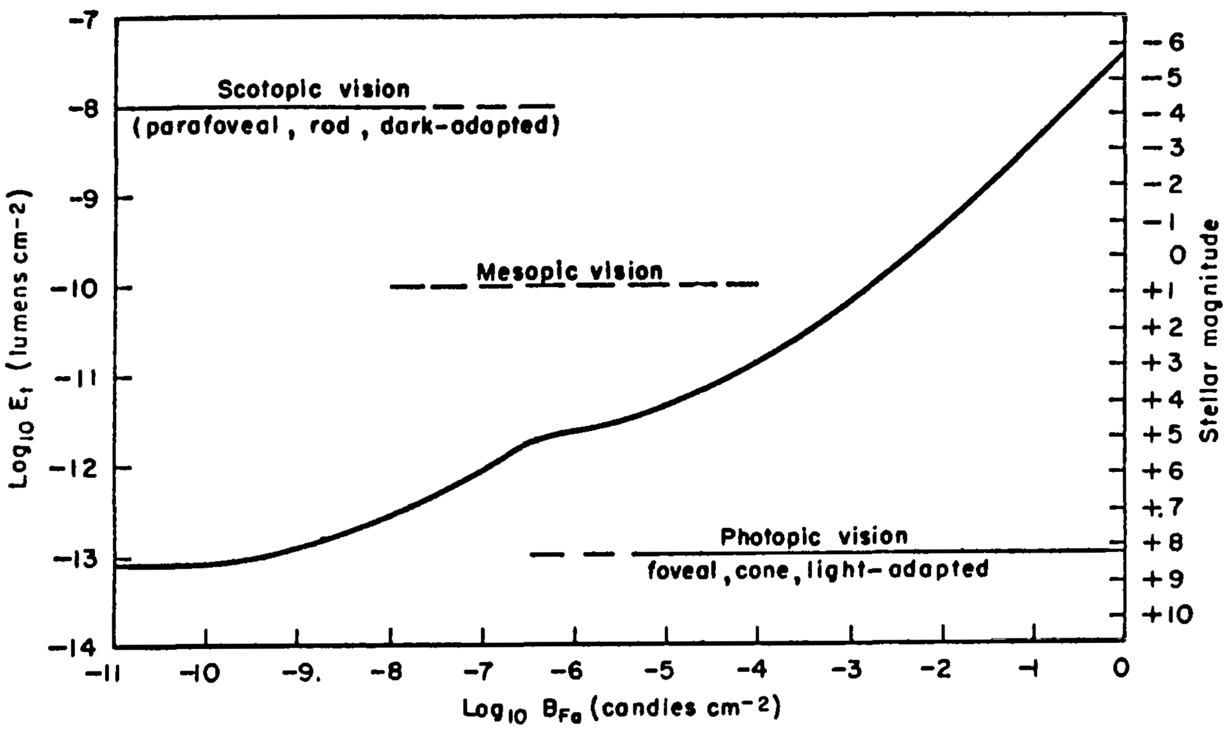
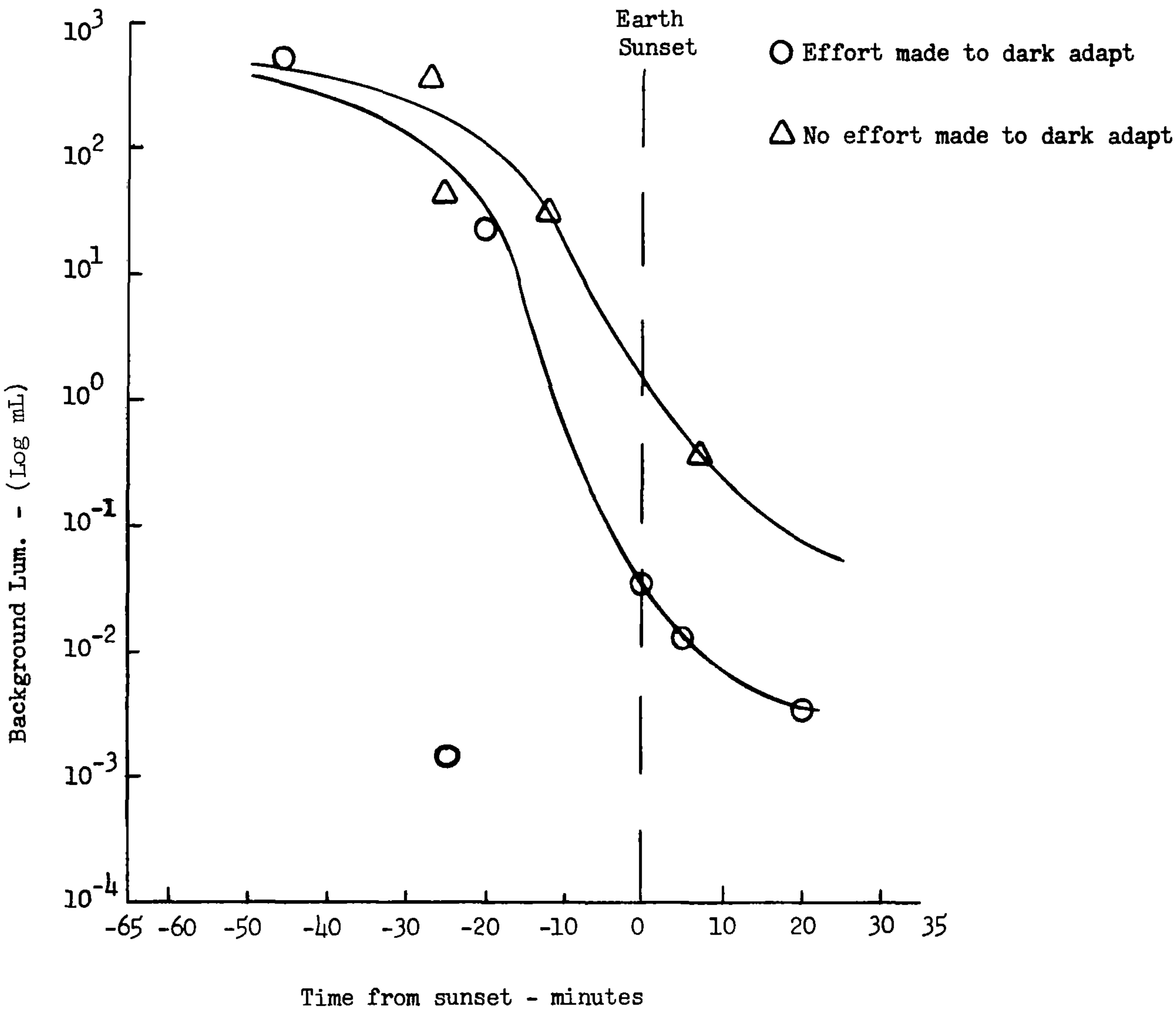


FIGURE 26: INFLIGHT TARGET VISIBILITY DATA FOR GEMINI FLIGHTS



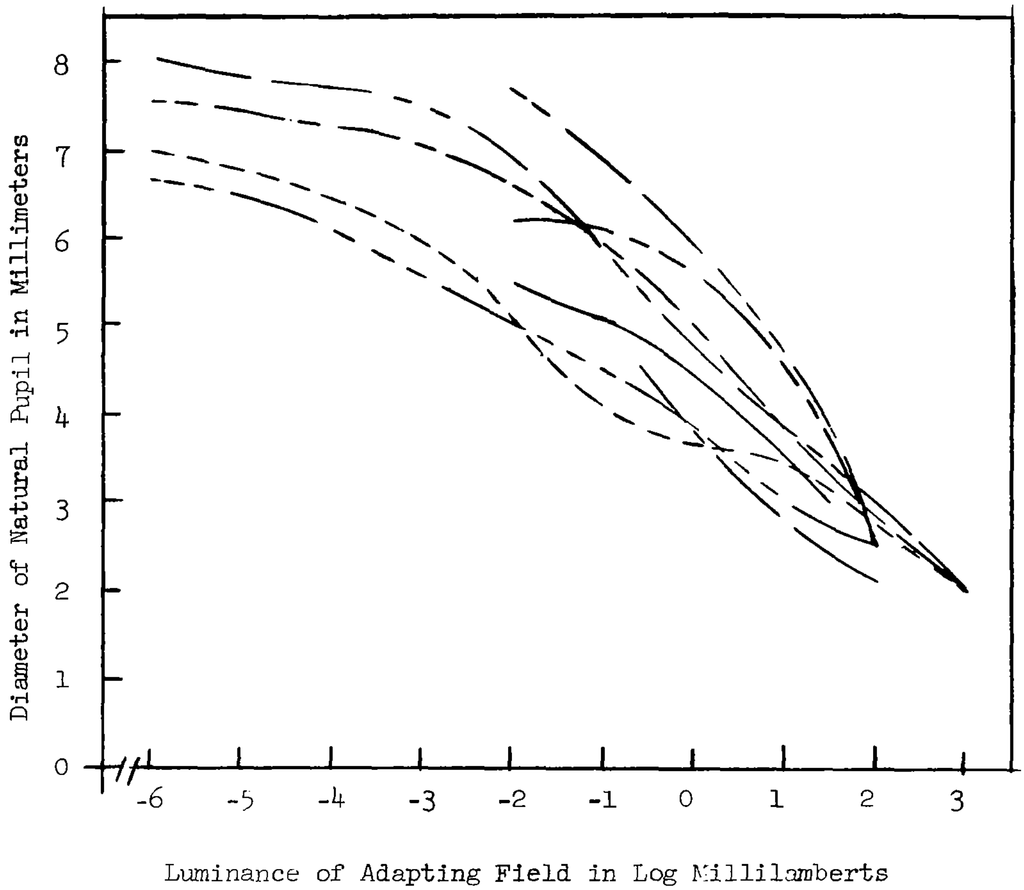


Fig. 27 - The Relationship of Pupil Size to Adapting Luminance (ref. 23).

This figure is scaled up from that presented by DeGroot and Gebhart and is not precise. The data are derived from eight different studies reported in the literature.

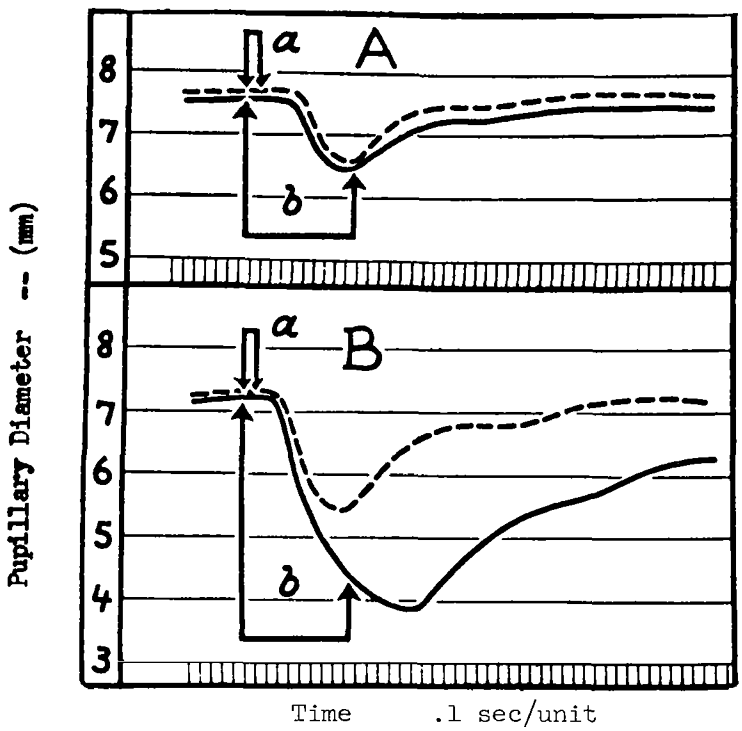


Fig. 28 **Pupil responses to a Short Flash of Light** (ref. 34)

The broken lines are responses to 0.1 second flashes (a). The solid lines (b) are responses to 1.0 second stimuli. The stimulus magnitudes were A-3ly units above scotopic threshold and B-9 log units above threshold.

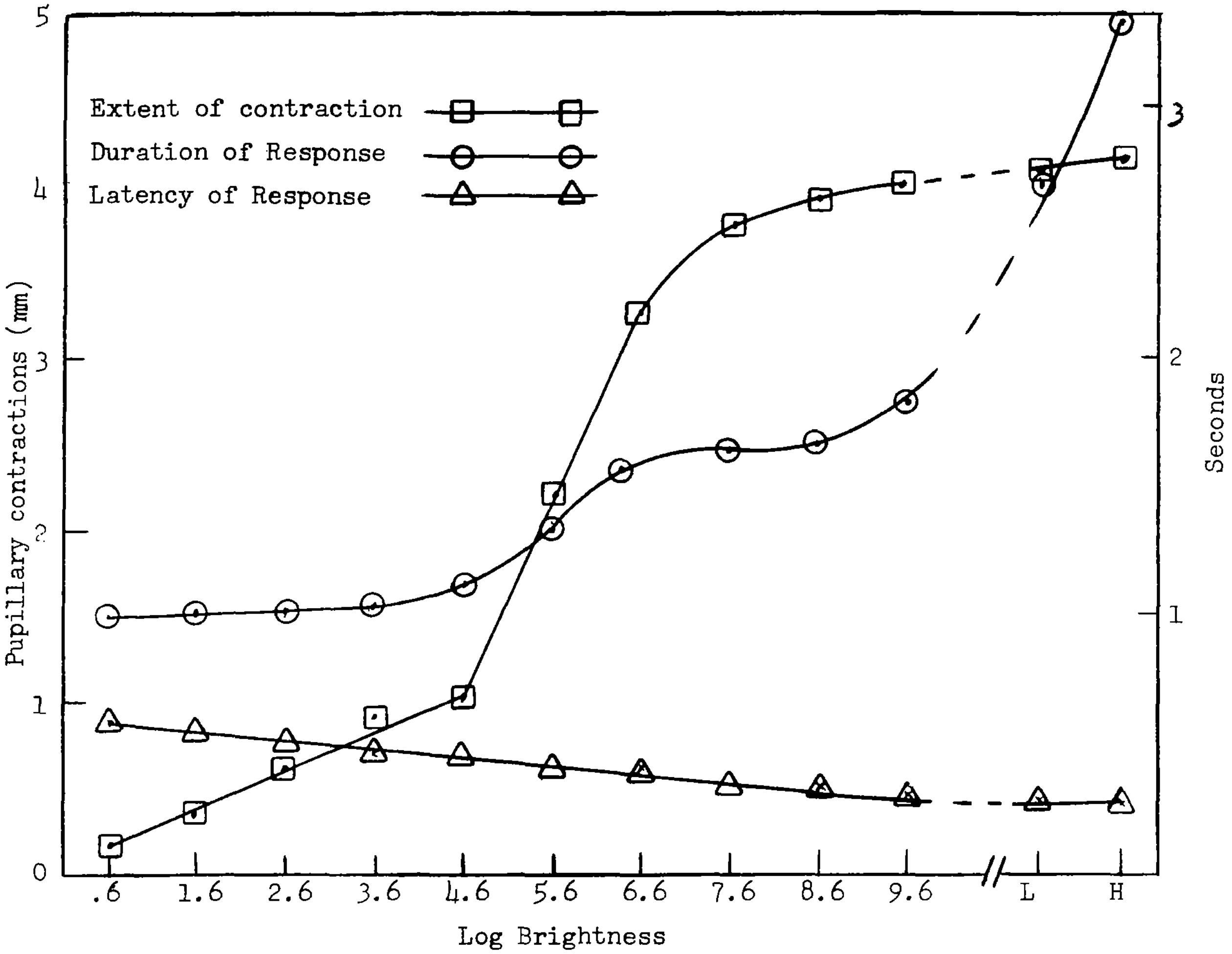


Fig. 29 - Amplitude, Duration and Latency of Pupil Responses to 1 Second Light Flashes (ref. 34).

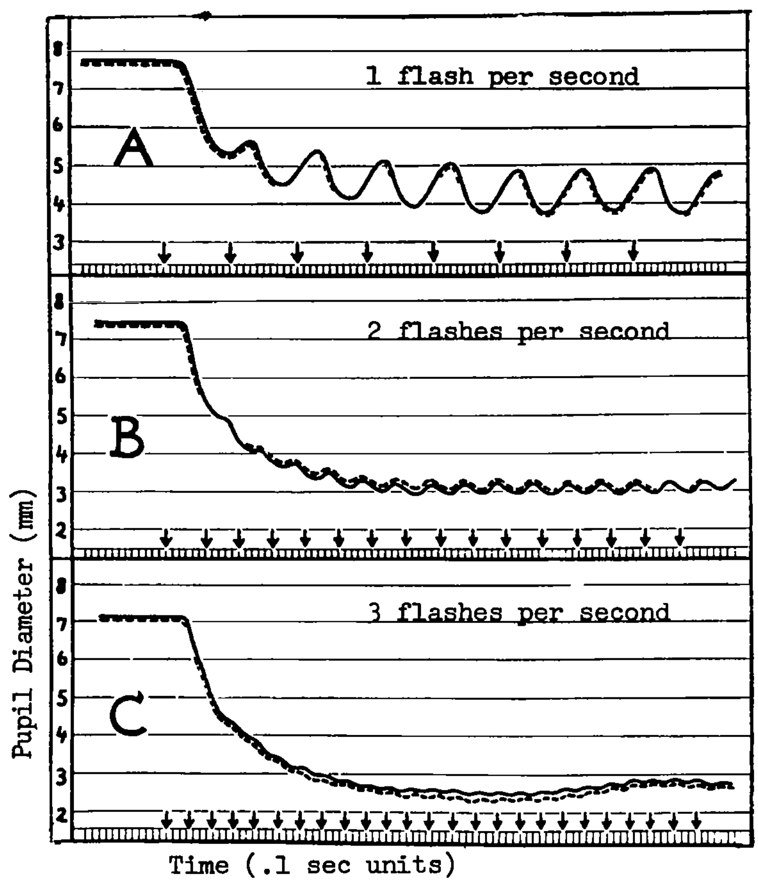


Fig. 30-Pupil Responses to a Series of Light Flashes (ref. 34)

flash duration - 5 msec

flash intensity - 9 Log units above scotopic threshold

5^{o} centrally fixated test patch

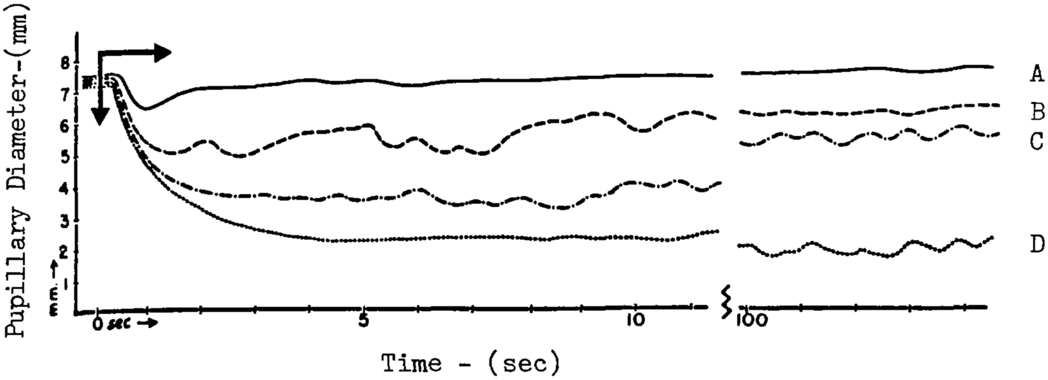


Fig. 31 - Pupil Responses to a Stepfunction Change in Luminance (ref. 34).

Curves A, B. C. and D represent response to stimulus intensities 2.6, 4.6, 6.6 and 8.6 log units above the scotopic threshold.

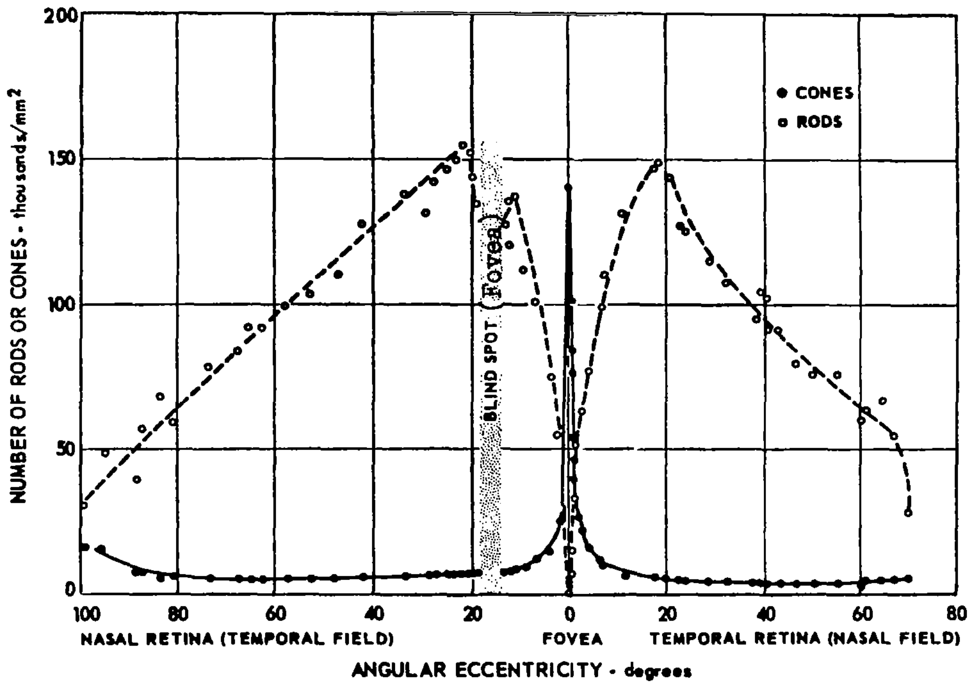


Fig. 32 - Distribution of Rods and cones in the Retina (ref.52).

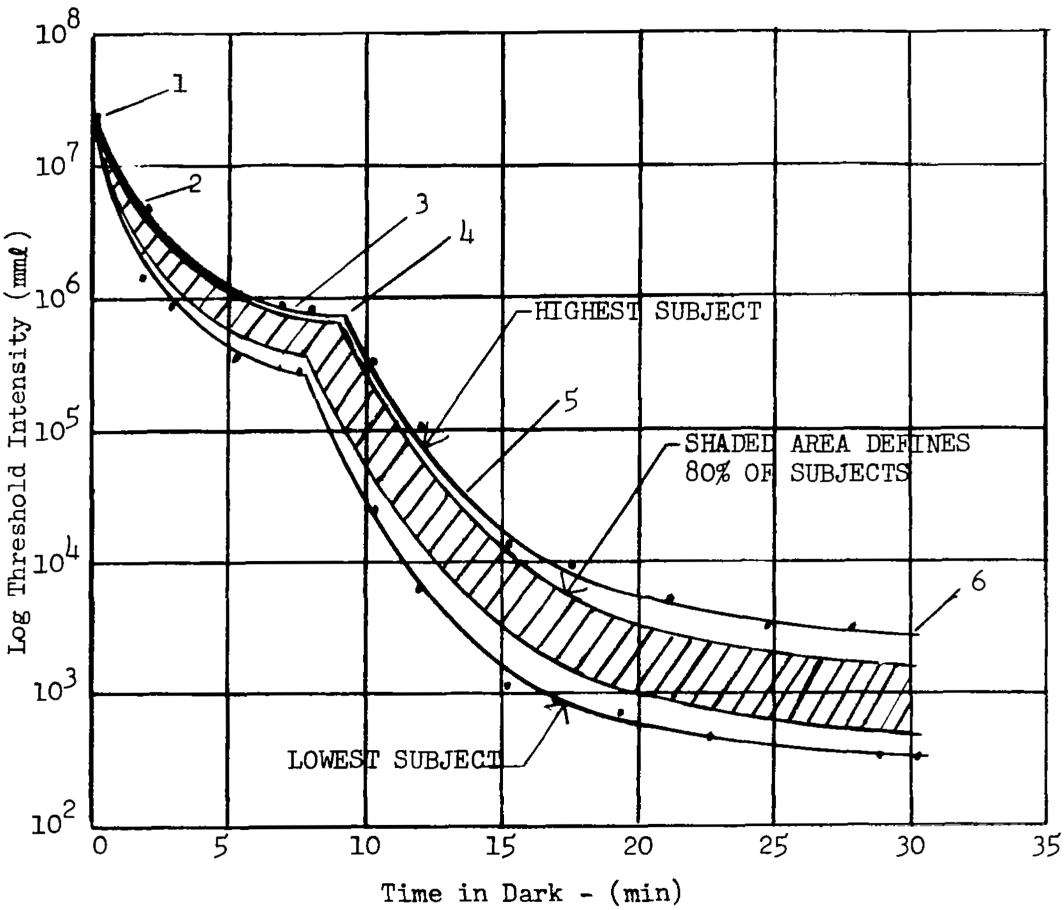


Fig. 33 - The General Course of Dark Adaptation (ref.43).

Area enclosed by the curve indicates the range of response in a sample of 110 subjects. Numbers on the curve correspond to categories listed by Anderson and presented in Table XVIII.

1. Initial Threshold	4. Rod-Cone Break
2. Cone Slope	5. Rod Slope
3. Cone Plateau	6. Rod Final Level

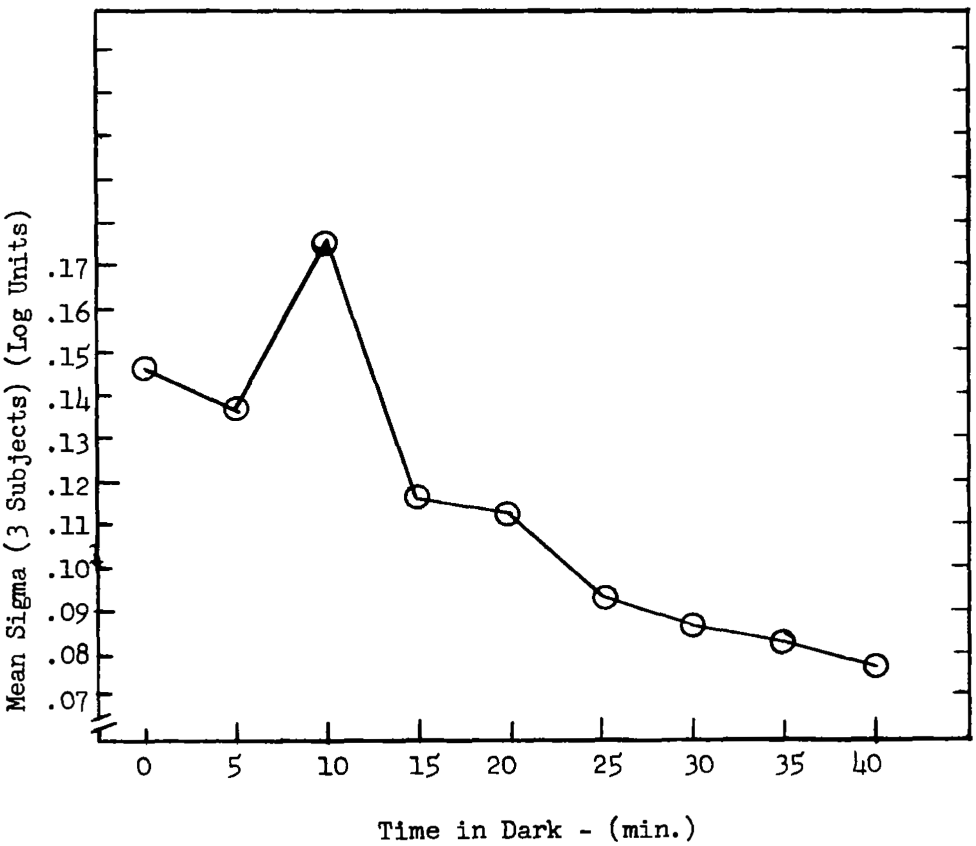


Fig. 34 - Variation in Dark Adaptation Over Repeated Measures on the Same Observers. (ref. 38)

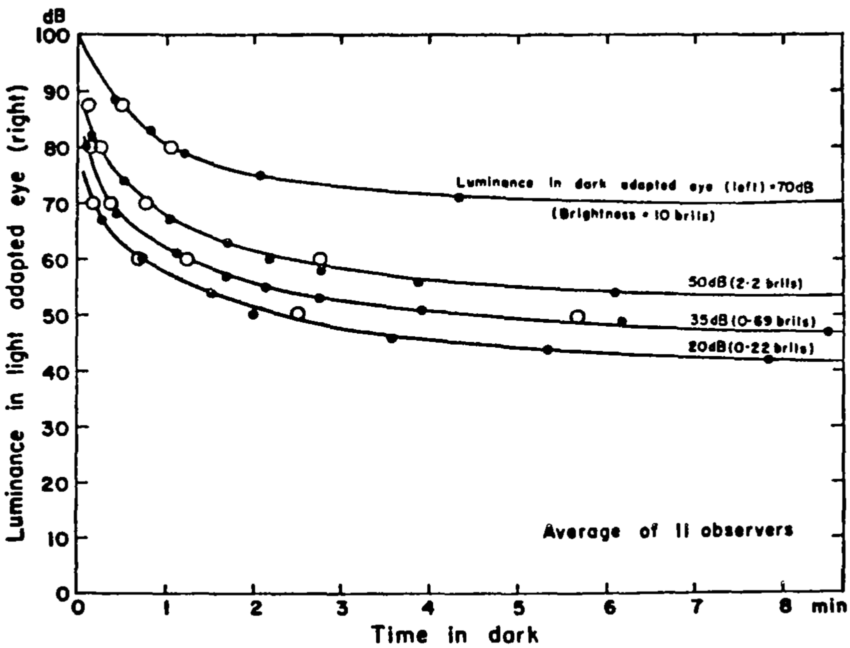


Fig. 35 - Luminance in the Light Adapted Right Eye Necessary for a Constant Level of Subjective Brightness as a Function of Time in Dark (ref. 47).

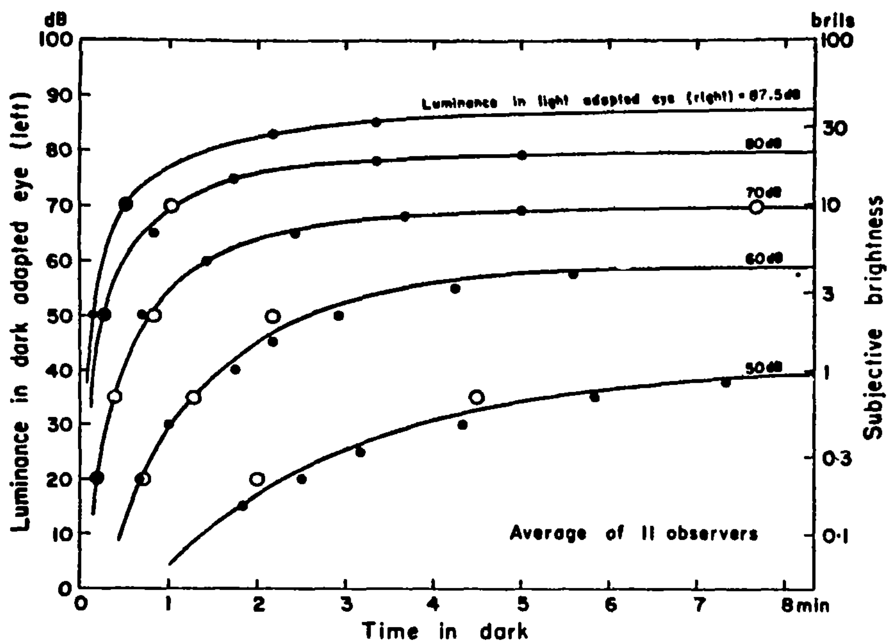


Fig. 36 - Subjective Brightness of Different Luminances in a Light Adapted Eye as a Function of Time in Dark (ref. 47).

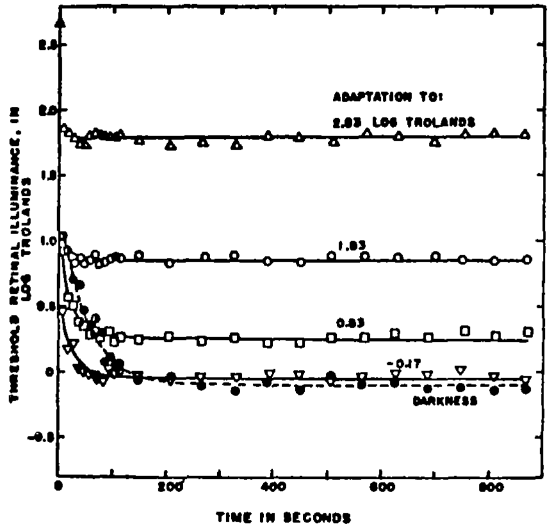


Fig. 37B: Dark adaptation of one subject to five intermediate levels of luminance eight degrees from the fovea in the temporal retina. (ref. 28)

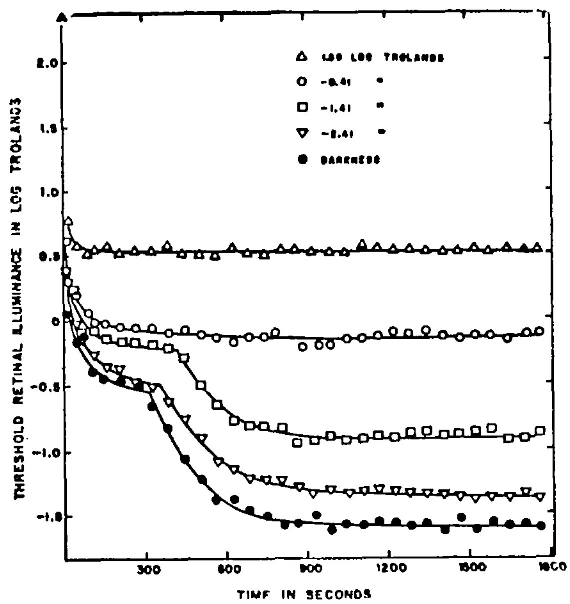


Fig. 37A: Dark adaptation of one subject to five intermediate levels of luminance in the fovea. (ref. 28)

Fig. 37 - Adaptation to Non-Zero Luminance Fields.

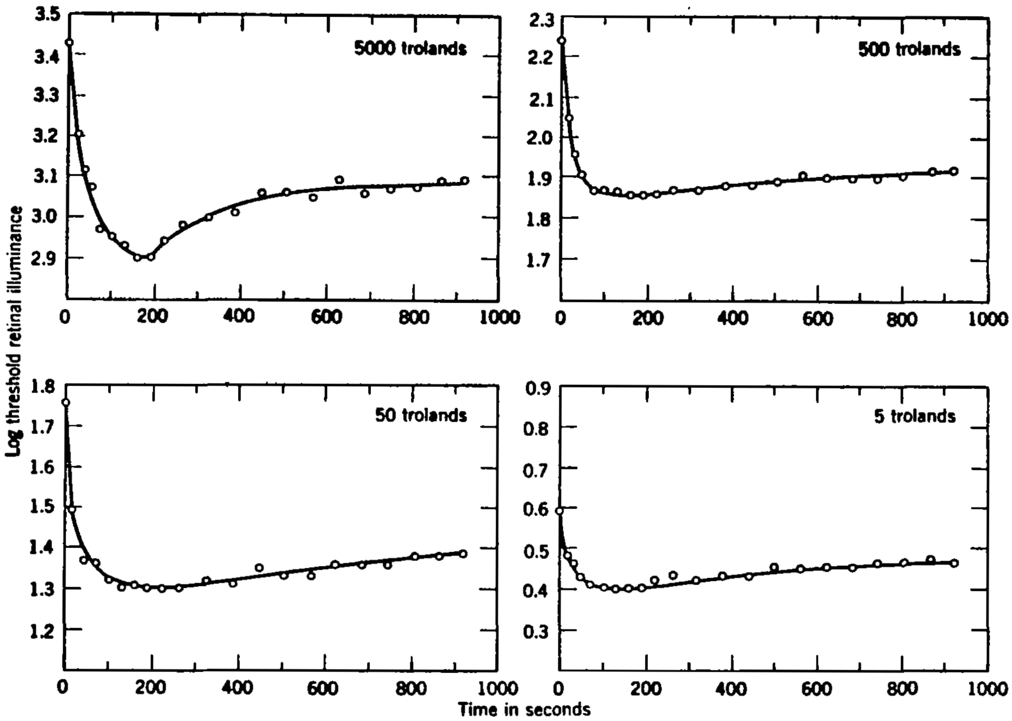


Fig. 38 - The General Course of Light Adaptation.

Threshold retinal illuminance as a function of time for exposure to four adapting illuminances (ref. 7).

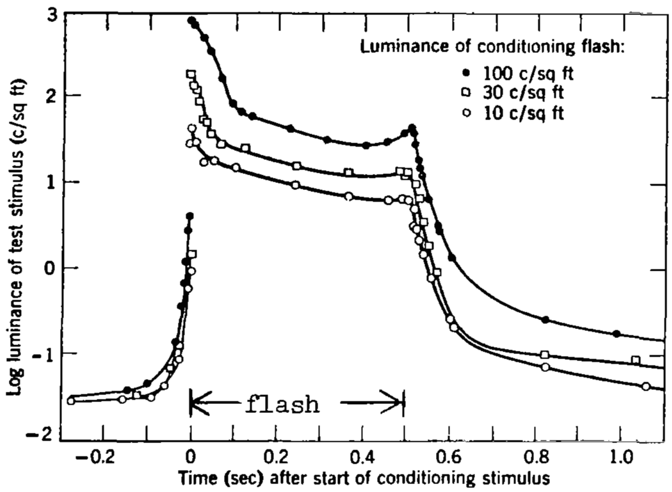


Fig. 39 - Immediate Responses to Illumination Transients in the Dark Adapted Eye (ref. 20).

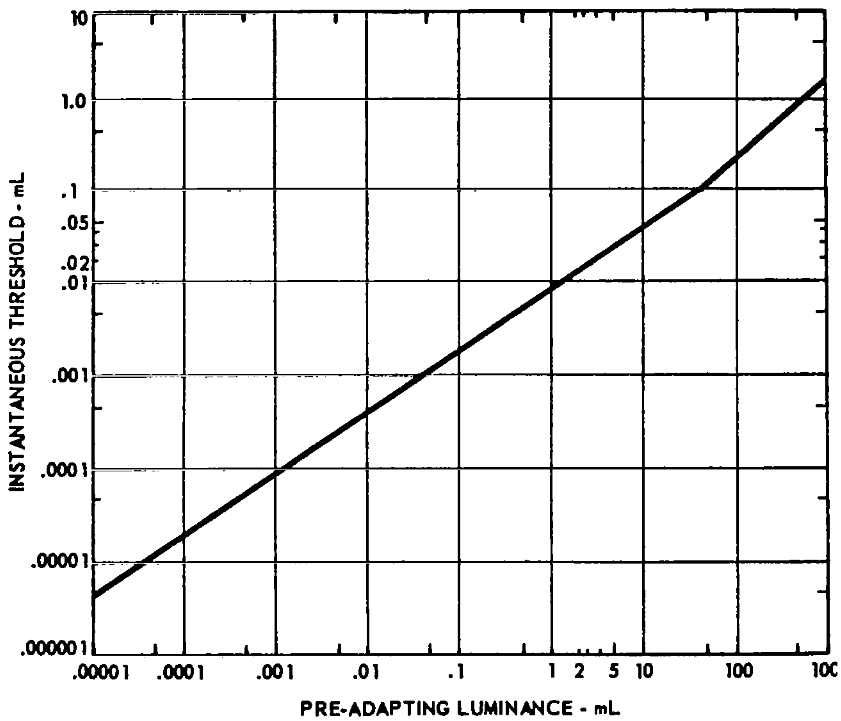


Fig. 40 - Instantaneous Threshold of the Eye (ref. 41).

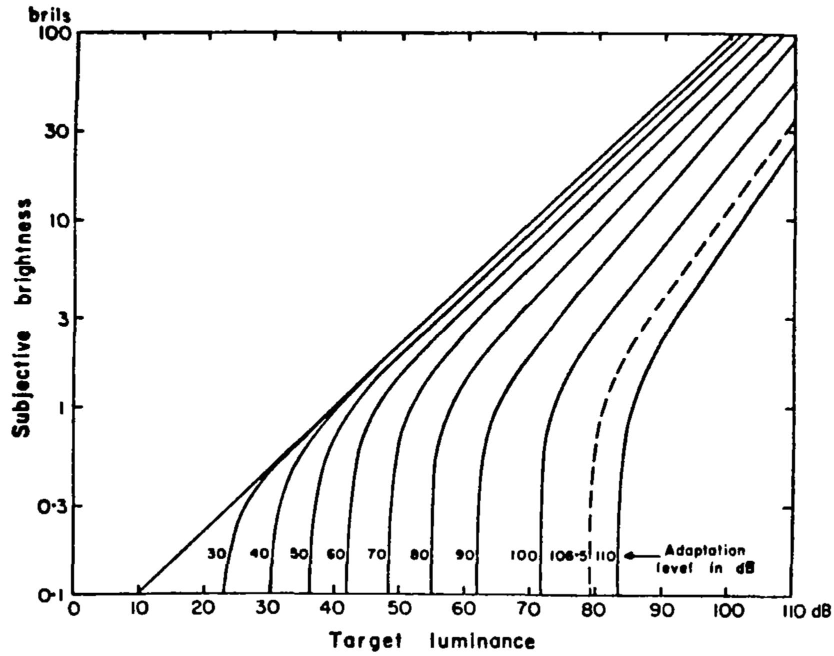


Fig. 41 - Operating Characteristics Produced by Different Levels of Light Adaptation.

The relationship between target luminance and subjective brightness immediately after an adapting field is switched off (ref. 47).

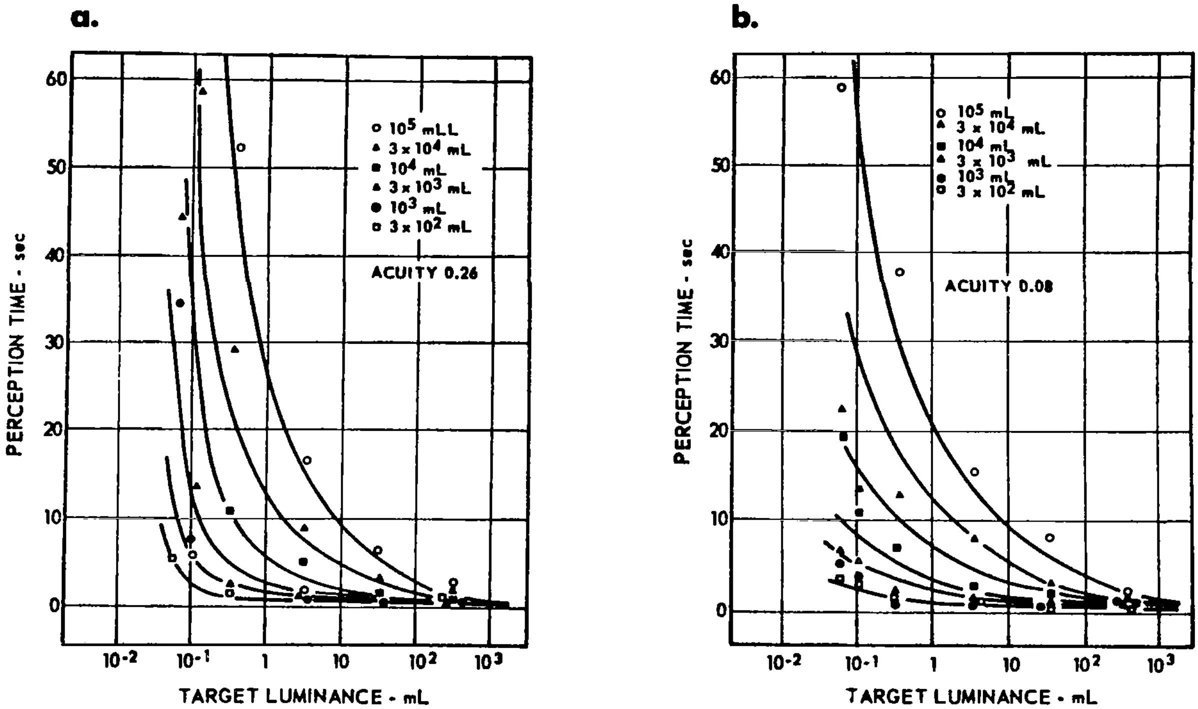


Fig. 42 - The Perception of Acuity Targets by the Dark Adapted Eye After Exposure to Brief Flashes of Light (ref. 14)

Flash intensities are indicated by coded symbols.

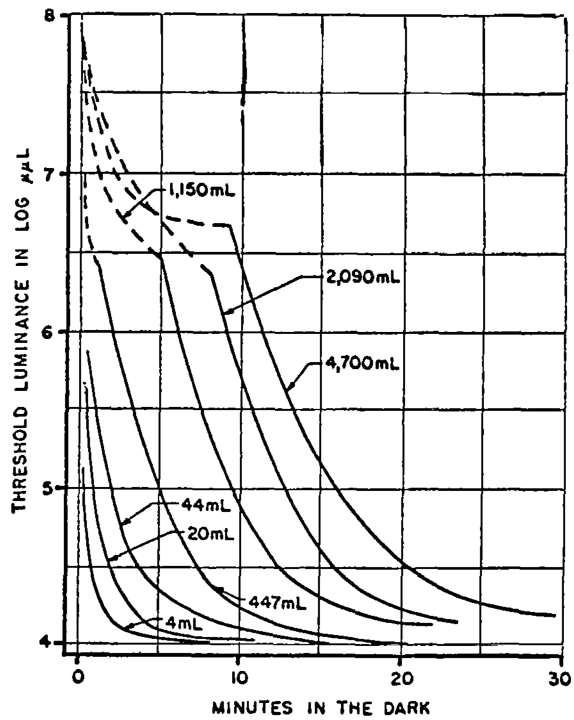


Fig. 43 - Dark Adaptation as a Function of Pre-Exposure Intensity (ref. 26)

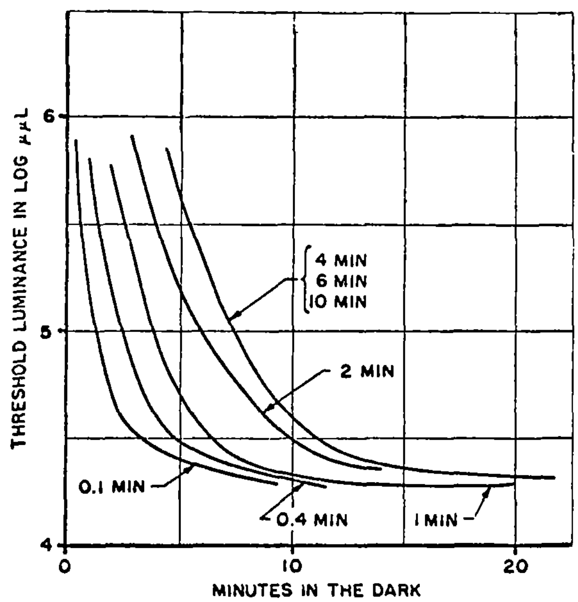


Fig. 44 - Dark Adaptation as a Function of Pre-Exposure Duration (ref. 26)

Dark adaptation following adaptation to 447 mL pre-exposure field for indicated durations.

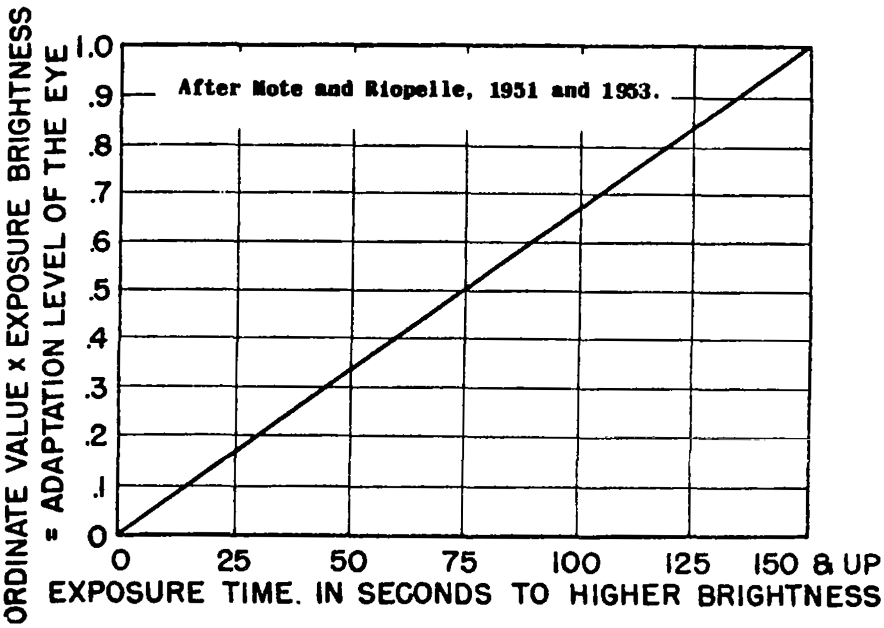


Fig. 45 Equivalent Steady State Adaptation Levels After Exposure to Short Duration Illumination (ref. 6)

"For any given exposure duration the value in the ordinate is used as a multiplier of the exposure brightness to give the steady state adaptation level of the eye."

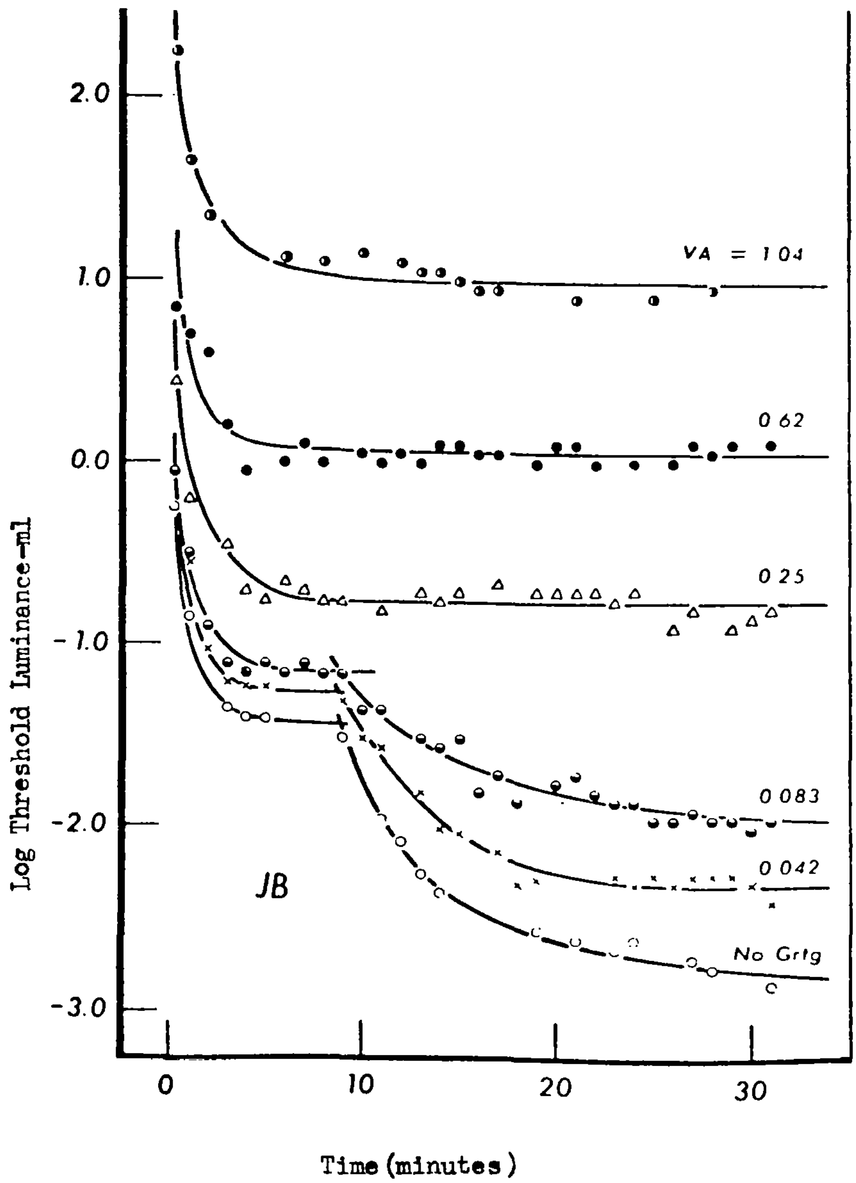


Fig. 46 Luminance Thresholds for Different Acuities During Dark Adaptation. (ref. 16)
Numbers beside each curve refer to levels of acuity.

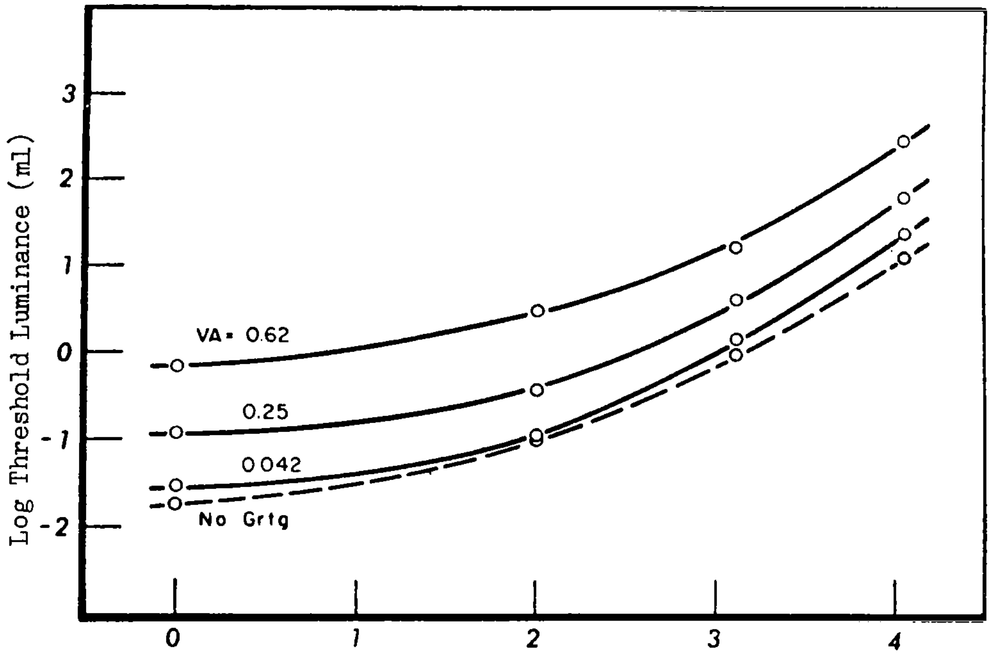


Fig. 47 - Luminance Thresholds for Different Acuities After One Second of Dark Adaptation (ref. 16)

The number beside each curve refers to the level of acuity.

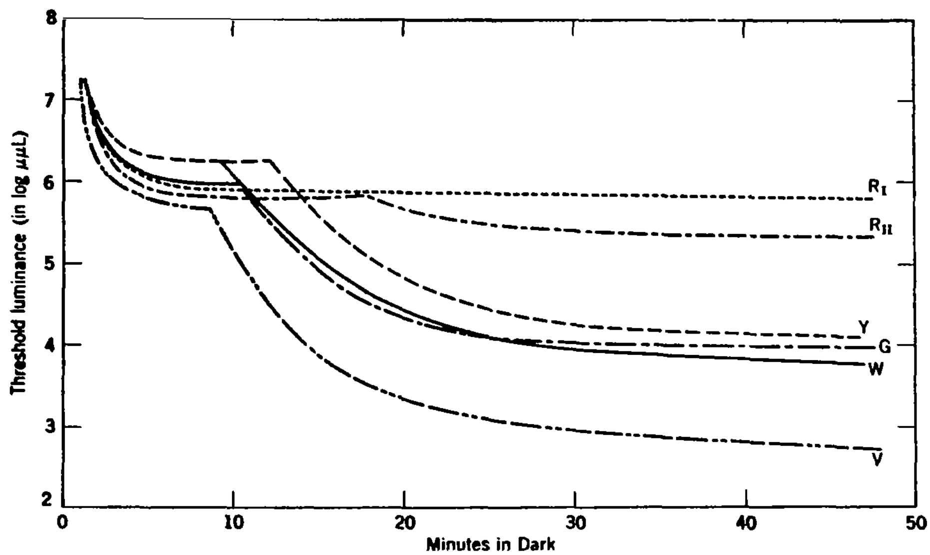


Fig. 48 - Dark Adaptation Measured by Test Flashes of Different Wavelengths (ref. 18)

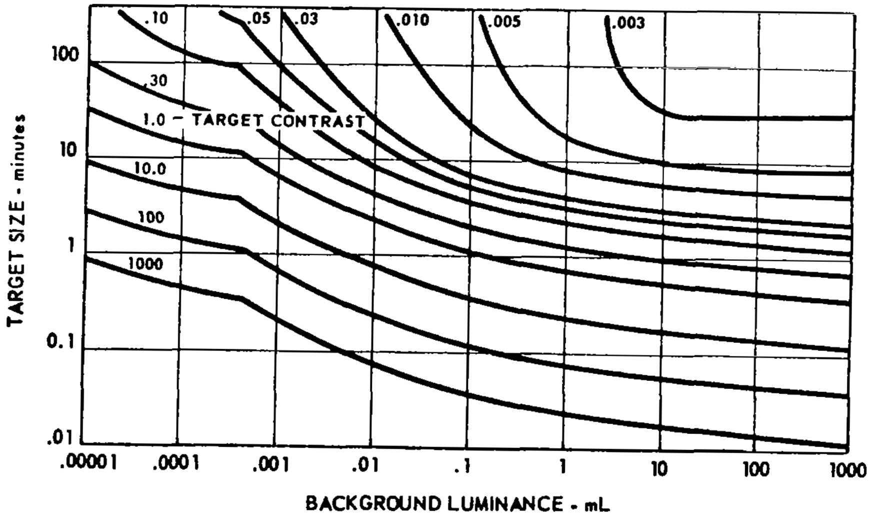


Fig. 49 - Threshold Target Angular Size as a Function of Contrast Ratio and Background Luminance (ref. 9)

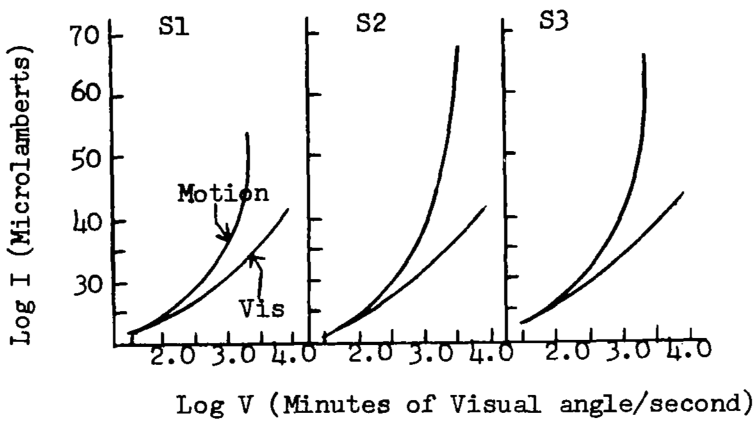


Fig. 50 Luminance Threshold for Visibility and Discrimination of Motion as a Function of Stimulus Speed. (ref. 10)

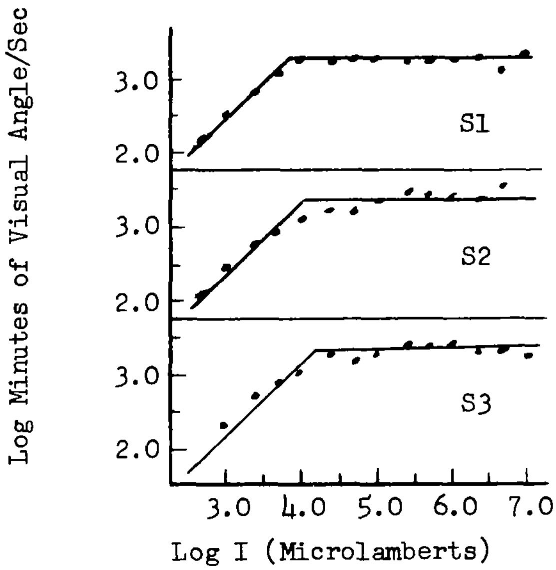


Fig. 51 The Upper Speed Threshold as a Function of Luminance. (Ref. 10)

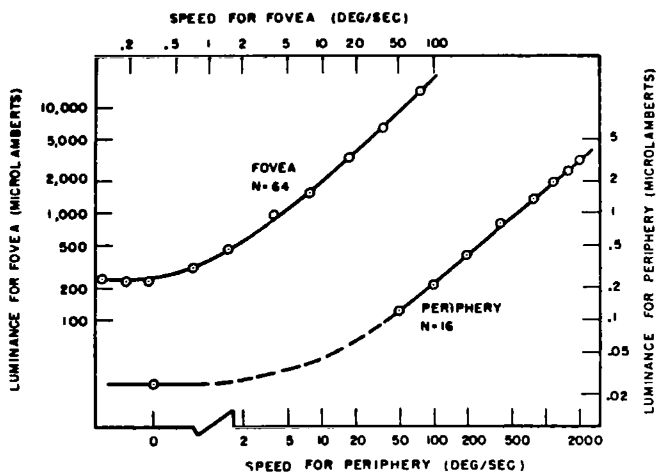


Fig. 52 Threshold Luminance as a Function of Speed. (Ref. 12)

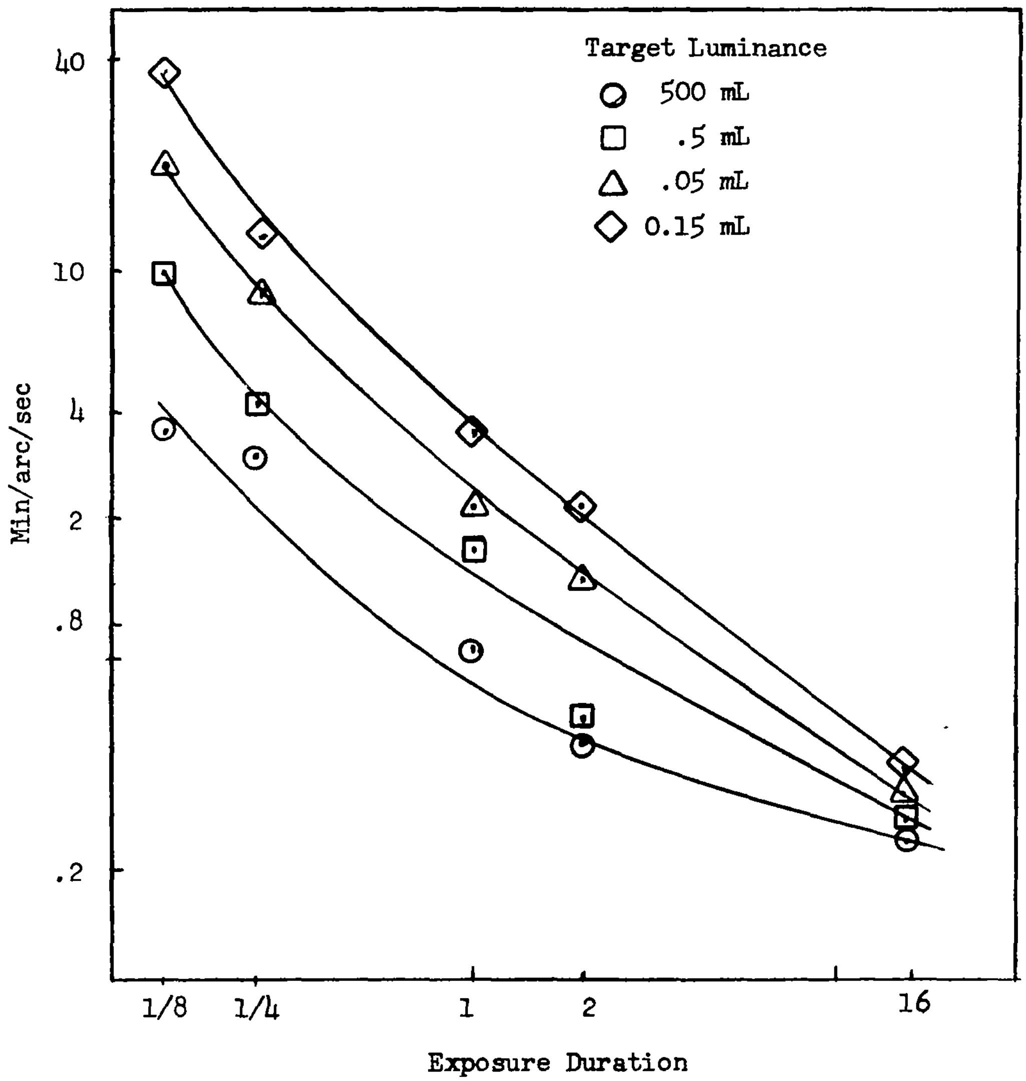


Fig. 53 Isochronal Threshold Velocity as a Function of Duration of Exposure With Luminance as a Parameter. (Ref. 31)

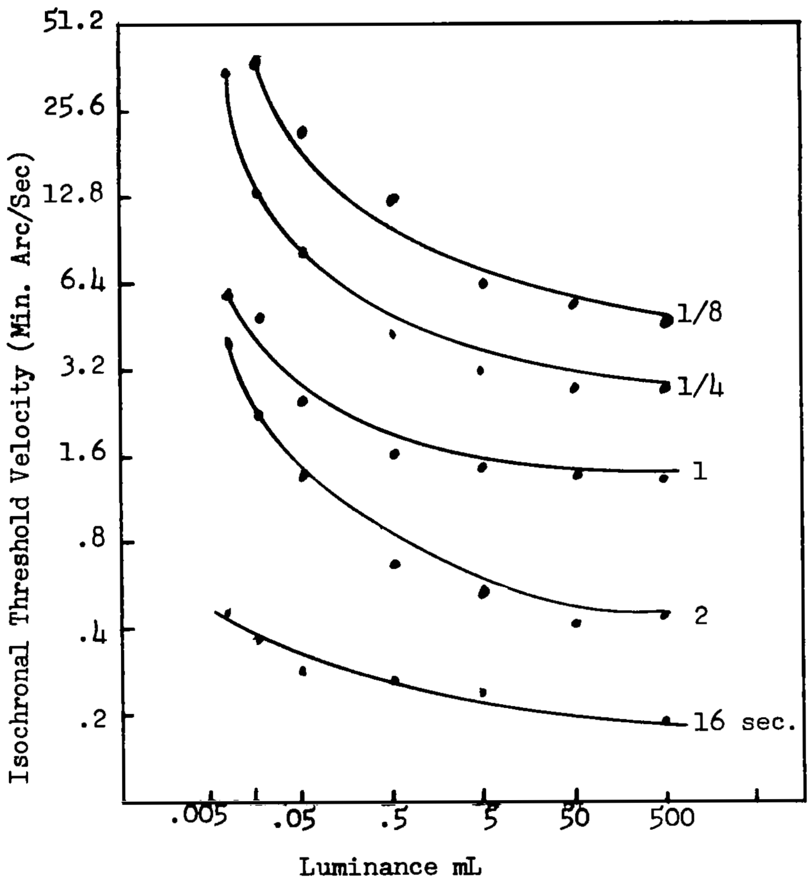


Fig. 54 Isochronal Threshold Velocity as a Function of Luminance With Duration of Exposure as a Parameter. (Ref. 31)

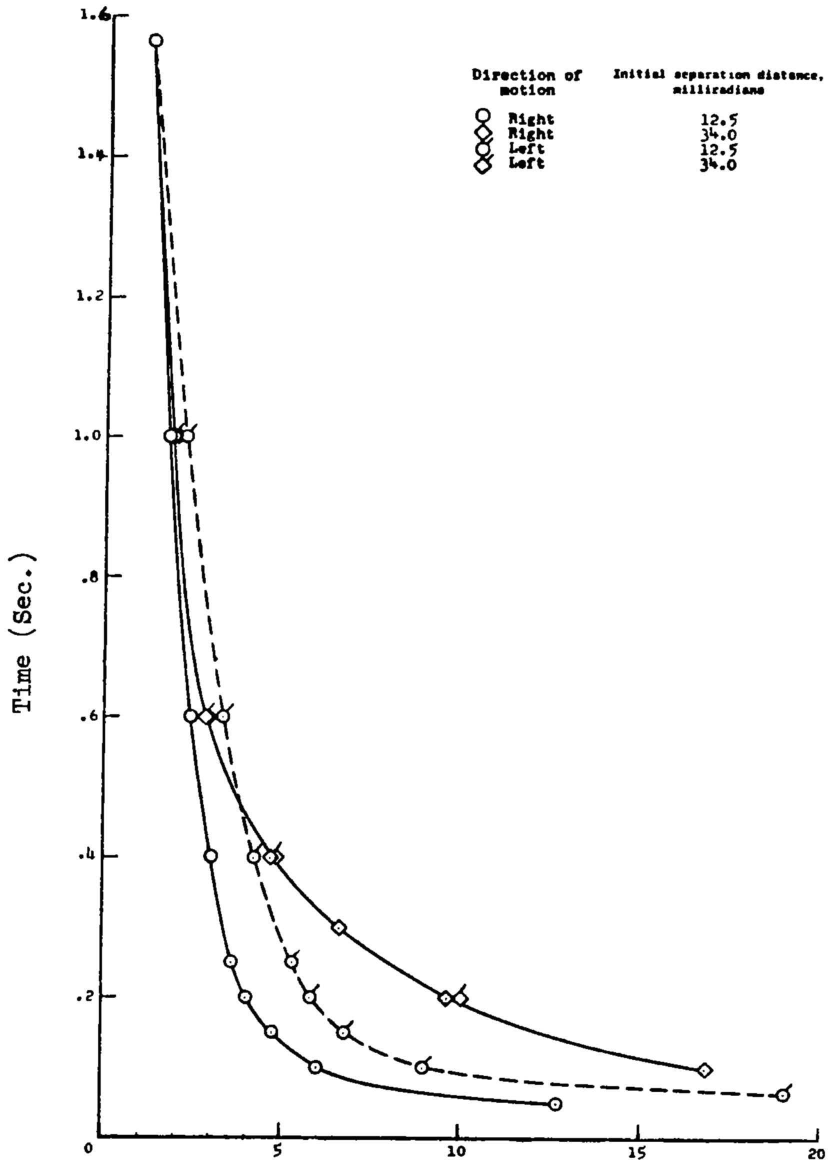


Fig. 55 Time to Identify a Moving Point as Function of Rate of Motion, Direction of Motion and Presence of Reference Points. (Ref. 5)

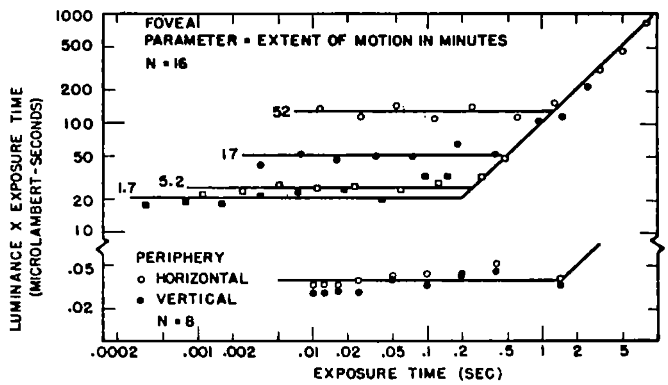


Fig. 56 Energy Required for the Visibility of a Moving Test Spot as a Function of its Exposure Time. (Ref. 12)

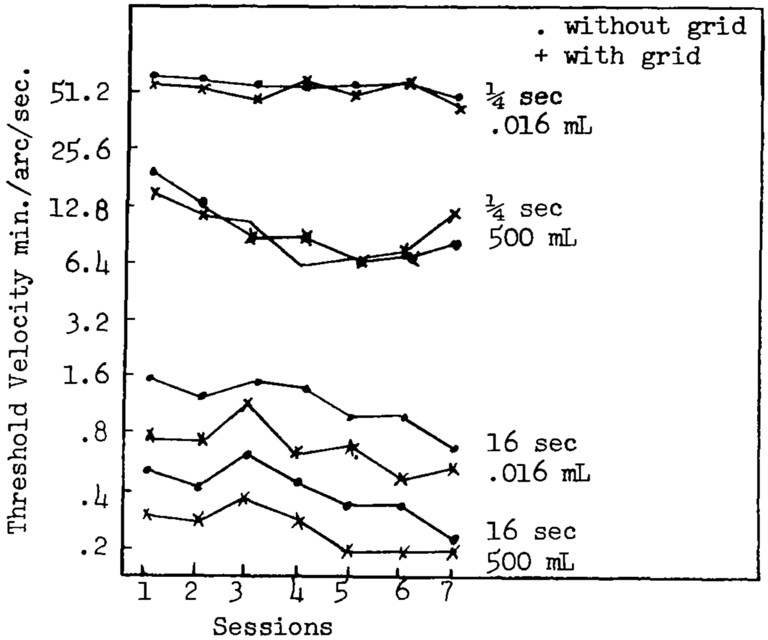


Fig. 57 Threshold Velocity as a Function of Practice With Duration of Exposure, Luminance, and Reference Points as Parameters. (Ref. 32)

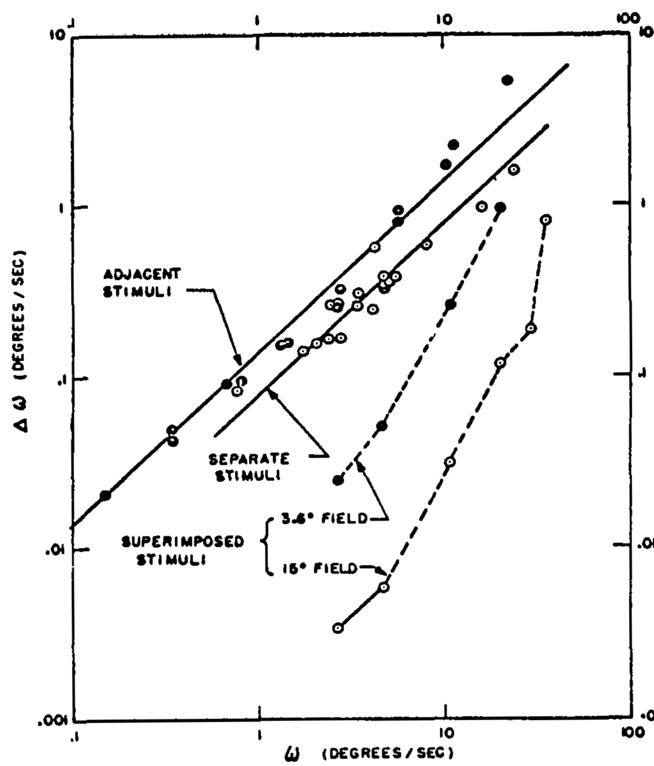
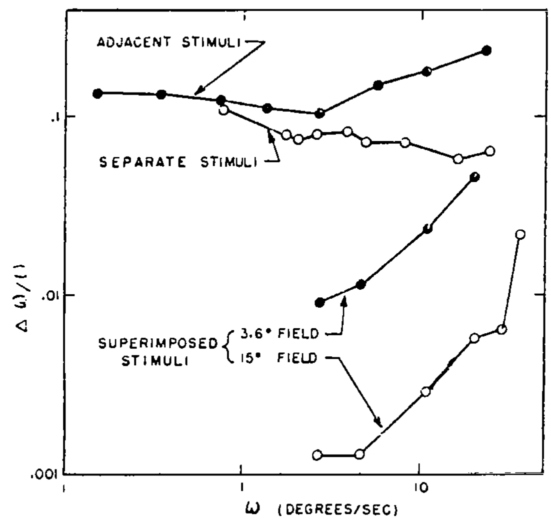


Fig. 58 The Differential Angular Speed Threshold ($\Delta\omega$) as a Function of Angular Speed (ω). (Ref. 14)



Superimposed stimuli yield much lower Weber ratio, e.g., .00128 for 2 needles traversing at 15° speeds 5 deg/sec. - 2 needles - Mono Parallax offset direct determiner of threshold.

Fig. 59 The Weber Ratio ($\Delta\omega/\omega$) as a Function of Angular Speed for Discriminating Adjacent, Separate and Superimposed Stimuli. (Ref. 14)

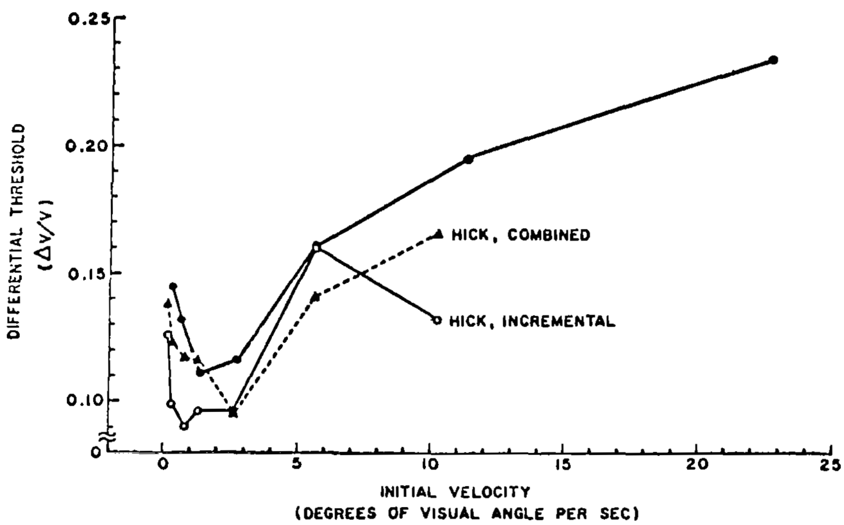
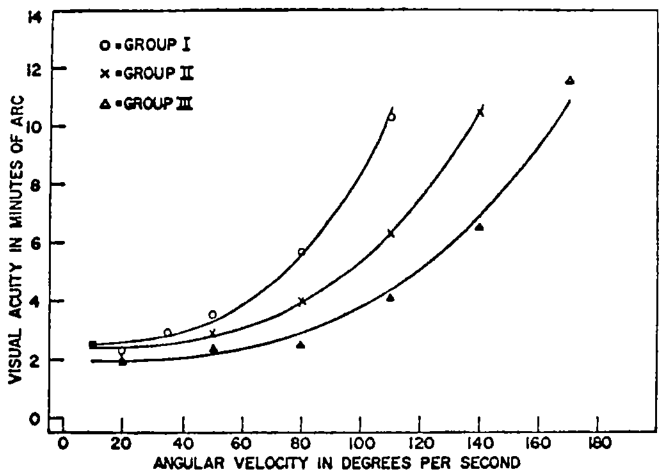


Fig. 60 The Instantaneous Threshold for Velocity. (Ref. 38)

EFFECT OF RELATIVE MOTION ON VISUAL ACUITY



1. Dependence of visual acuity on angular velocity of the test object

Fig. 61 Dynamic Visual Acuity as a Function of the Angular Velocity of the Test Object. (Ref. 36)

EFFECT OF RELATIVE MOTION ON VISUAL ACUITY

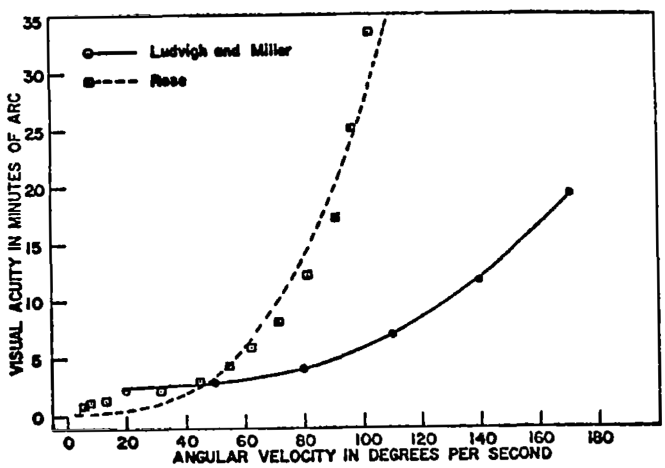


FIG. 2. Effect of change of exposure time

Fig. 62 The Effect of Isometric and Isochronal Test Procedures on Thresholds for Dynamic Visual Acuity. (Ref. 36)

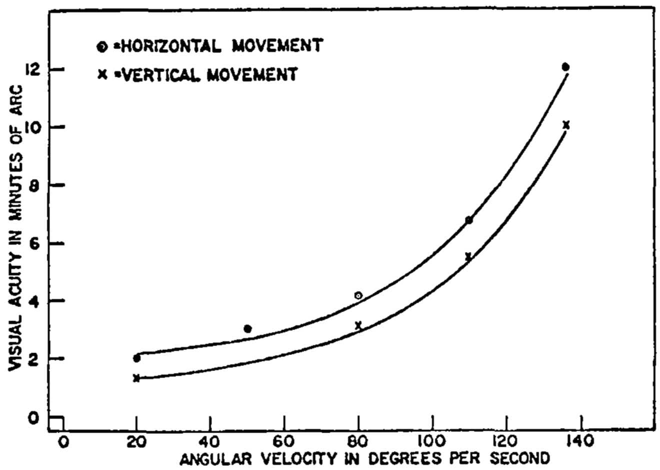


FIG. 3. Effect of direction of motion of the test object

Fig. 63 The Effect of Direction of Stimulus Motion on Dynamic Visual Acuity. (Ref. 36)

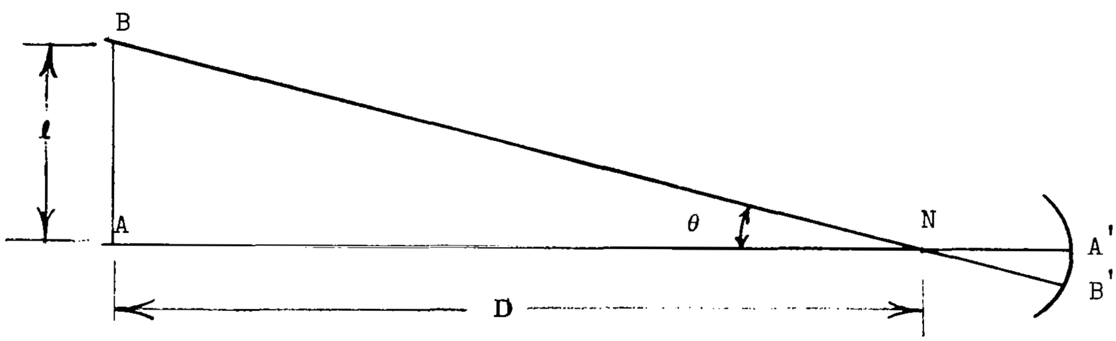


Fig. 64 Geometry of Size-Distance Relationship.

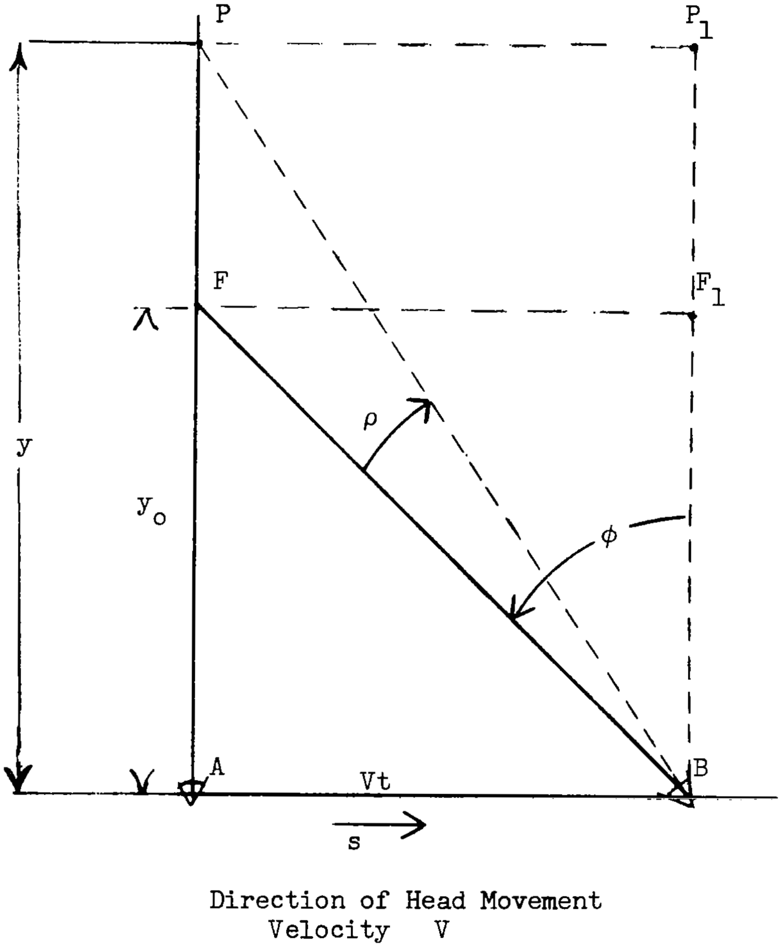


Fig. 65 Geometrical Relations Involved in Parallax. (Adapted from Ogle, ref. 16)

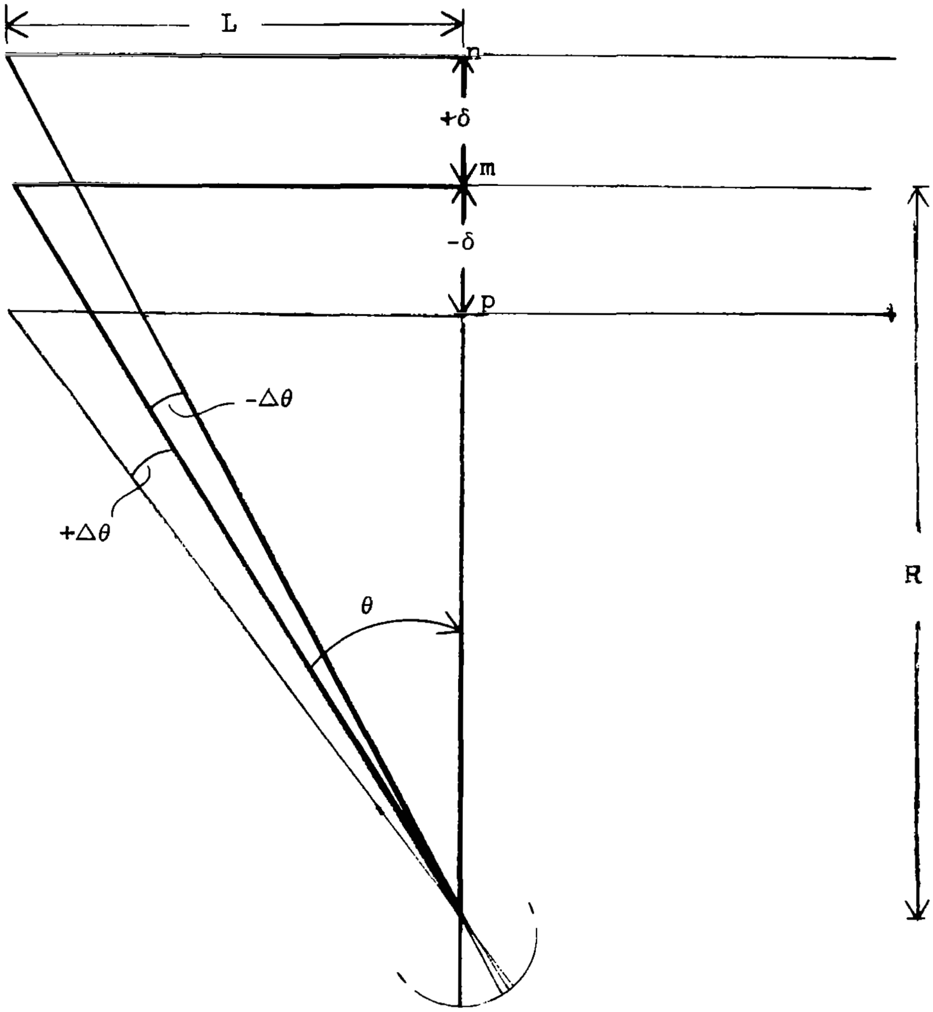


Fig. 66 Geometrical Relations in Parallax with Eye Fixed and Object-Points Displaced. (After Graham, et al., ref. 32, p. 206)

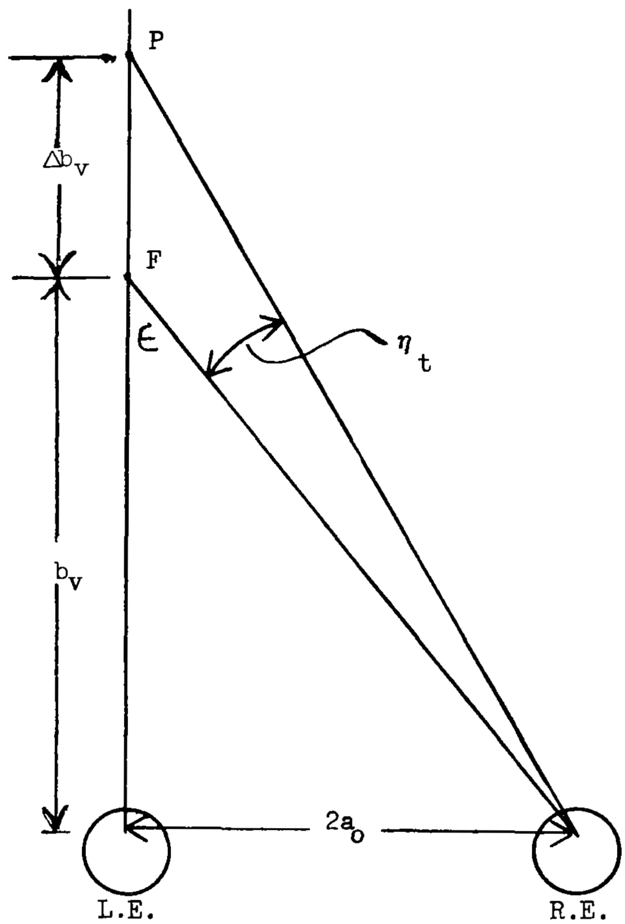


Fig. 67 Geometrical Relations in Stereopsis.

Appendix A
SYMBOLS

A	area
A_p	maximum limit of perceived distance for a given observer
A_s	solid angle subtended by light entering the eye
a	Blondell-Rey factor
a_o	one half the interocular distance
B	background brightness
Ba	apparent object brightness
B_t	target brightness
b	slope
b_L	maximum viewing distance for stereopsis
b_v	viewing distance
C	contrast ratio
D	object distance
D_f	luminous flux density at the pupil
D_i	objective diameter
D_o	eye pupil diameter when adapted to true background brightness
d_p	perceived distance
d_o	space correction factor
E	illumination at the eye
E_f	flashing source illumination at the eye which appears as bright as E
E_o	solar illumination at the earth/moon distance (one solar constant)

E_r	retinal illumination
E_v	"veiling" illuminance at the eye due to a glare source
F_e	net effective flux for any pupil radius
G	optical gain
h	orbit altitude
h_a	earth "aura" altitude
I	source light intensity (steady source)
I_f	flashing source intensity required
K, K_i	curve fitting constants
L	target luminance
L_o	minimum perceptible display luminance
ℓ	object length
M	mean threshold angular rate
M_ℓ	linear magnification
m	stellar magnitude at sea level
m_c	chase vehicle mass
P_o	orbit period
R	range between chase and target vehicles
R_f	distance to fixation point from eye
R_t	target distance from orbit center
$\dot{R}$	range rate between chaser and target vehicles
r	radius
r_e	earth radius
r_p	pupil radius

T optical transmission

T_n thrust vector

t time

t_d time in dark

t_L recovery time for visual sensitivity after a flash of light

t_p Light flash duration

V change in velocity during presentation time of target

V_s subjective velocity determination

$\overline{V}$ mean velocity during target presentation time

α angle of elevation of line of sight

α_i angle between incident light and light reflected into eye (see Table VI)

$\dot{\alpha}$ elevation angular rate of line of sight

β azimuth angle of line of sight

β_i angle between surface normal and light reflected into the eye (see Table VI)

$\dot{\beta}$ Azimuth angular rate of line of sight

Δb_v depth interval (Ogle)

Δ_θ parallax angle (Graham)

Δ_ω angular rate change required for a perception of a change in target position

δ depth interval (Graham)

δ_c cone half angle (see Table VI)

η stereoscopic angle (Ogle)

η_t stereoptic threshold angle

θ angle between chaser line of sight and local horizontal through target vehicle

θ_i angle between sun light incidence angle and local surface normal (see Table VI)

θ_o initial (θ)

θ_r angle of rotation of eye

θ_s angle subtended by object at the eye (visual angle)

θ_v angle between fixation point and glare source

μ gravitational constant

ρ parallax angle (Ogle)

ρ_r reflectance

ρ_t chaser distance from target orbit center

σ standard deviation

τ window transmittance

ϕ angle of rotation of eye (Ogle)

ψ angle between local surface normals (see Table VI)

ω angular rate of target motion

ω_e earth rotation frequency

ω_t parallax differential angular velocity threshold

Appendix B

CONVERSION FACTORS

In the following tables 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		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/ft^2	Lumens/meter^2
Footcandles	1	10.764	1	10.764
Meter-candles	0.0929	1	0.0929	1
Lumens/ft^2	1	10.764	1	10.764
Lumens/meter^2	0.0929	1	0.0929	1

LUMINANCE

(Surface brightness or reflected light)

	Candles foot^2	Candles/meter^2	Footlamberts	Apostilbs***	Lamberts (Lumens/cm^2)
Candles/foot^2	1	10.764	π	10,764	$\frac{\pi}{929}$
Candles/meter^2	0.0929	1	0.0929	π	$\pi \times 10^{-4}$
Footlamberts	$\frac{1}{\pi}$	$\frac{10.764}{\pi}$	1	10.764	10.764×10^{-4}
Apostilbs***	$\frac{0.0929}{}$	$\frac{1}{\pi}$	0.0929	1	10^{-4}
Lamberts (Lumens/cm^2)	$\frac{929}{\pi}$	$\frac{10^4}{\pi}$	929	10^4	1

QUANTITY OF ENERGY RECEIVED BY A SURFACE

	Meter-candle Seconds	Footcandle-Seconds	Ergs/cm^2	Watt-seconds/cm^2 or Joules/cm^2
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/cm^2	0.680 (at 555mμ*)	0.0632 (at 555mμ*)	1	10^{-7}
Watt-seconds/cm^2 or Joules/cm^2	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 $\times 10^{-7}$ (at 555mμ**)
Candlepower-Seconds	4	1	0.005882 (at 555mμ**)	0.005882 $\times 10^{-7}$ (at 555mμ**)
Watt-seconds of Joules	680 $\times 10^7$ (at 555mμ*)	$\frac{170}{\pi}$ (at 555mμ*)	1	10^{-7}
Ergs	680 $\times 10^7$ (at 555mμ*)	170 $\times 10^7$ (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 meter^2; occasionally incorrectly called meter-lambert.