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Jeffrey J. Armentrout

1 Lt , U. S. Air Force

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An Investigation of Stereopsis

with AN/AVS-6 Night Vision Goggles

at Varying Levels of Illuminance and Contrast

by

Jeffrey J. Armentrout

Thesis submitted to the Faculty of the

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in

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APPROVED:

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Blacksburg, Virginia

An Investigation of Stereopsis with AN/AVS-6 Night Vision Goggles at Varying Levels of Illuminance and Contrast

(ABSTRACT)

by

Jeffrey J. Armentrout

Committee Chairman: Robert J. Beaton

Industrial and Systems Engineering

The increased reliance on night operations by the military over the last few decades has led to the development of various night imaging devices. Night vision goggles (NVGs) are one device which have gained widespread use in nighttime helicopter operations. However, rotorcraft accident data have indicated an increased occurrence of "pilot error" type accidents when NVGs are in use. NVG related accidents often can be linked to extremely poor ambient lighting and contrast conditions during nighttime operations as well as the imaging limitations of the NVGs. Research has shown that NVGs reduce visual acuity and depth perception when compared to unaided daylight viewing conditions.

In this study the effects of illumination and contrast on stereoscopic vision with and without AN/AVS-6 goggles were investigated. Stereoacuity was measured using a modified Howard-Dolman apparatus with four levels of illumination and three levels of contrast. Testing was

performed with NVGs for nighttime illuminations and unaided for daytime levels of illumination. Image measurements were performed on the NVGs to determine the impact of illumination on resolution and signal-to-noise ratio.

Stereoscopic vision with NVGs was found to be significantly worse than under daylight conditions. Low levels of contrast also were found to reduce stereoacuity significantly. It was found that the worst stereoacuity in this study occurred under half moon or higher illumination levels. This research revealed that further NVG development should focus on the limitations of the NVGs under high light levels, and special considerations should be made for using NVGs in low contrast, high luminance situations.

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INTRODUCTION

Since 1971, military aviation has utilized night imaging systems to enhance night flying capabilities (Rash, Verona, and Crowley, 1990). While such systems have greatly increased the military's ability for 24 hour operations, safety concerns related to the use of night vision goggles (NVGs) continue to be debated. As the use of NVGs in aviation has increased, so too has the number of accidents during these operations (Boyd, 1991). While some would speculate that the increased accident rate correlates directly with the increased use of NVGs during night flying, others would argue that many accidents can be attributed to the limitations of the night imaging systems themselves.

An aviation mishap summary (Verona, 1988) cited several causes of NVG-related accidents, which included a lack of contrast and visual cues, flying too fast for the visual conditions present, an inability to determine distances to obstructions, and the invisibility of wires. Boyd (1991) investigated Army rotorcraft accidents (Class A-C) between Fiscal Years 1984 and 1989. Of the 626 accidents during this time, 23 percent occurred at night; and, of these accidents, 82 percent were attributable to crew error with 70 percent occurring while NVGs were in use. Of the 199 accidents resulting in fatalities, 41 percent took place at night, with 85 percent being associated with crew error. Of those fatal night accidents attributed to crew error, 71 percent occurred while NVGs were in use. The use of the human error classification in accidents often is used when some breakdown in the human-machine system has occurred that cannot be explained readily, and the investigators are looking for an easy explanation to a complex situation (Smith and Fedor, 1984). The classification of these NVG-related accidents as "crew error" is an indication that the night imaging systems have limitations and may be a contributing factor in these accidents.

Operations in a nighttime environment pose many risks to pilots, which may be reduced through the use of night imaging devices. It is imperative to understand that NVGs do not turn night into day. The image displayed by NVGs allow low altitude operations at night, but the overall impacts on visual perception and pilotage as compared to daylight are not fully understood (Biberman and Alluisi, 1992).

Biberman and Alluisi (1992) break the modern NVGs into four primary components:

1. A mounting frame to hold all the components,
2. An objective lens to focus the night image onto the photocathode,
3. A channel-plate proximity-focused image-intensifier, and

4. A magnifying eyepiece with focusing adjustments to display the intensified image to the viewer.

The optics of NVG systems consist of conventional unity magnification simple lenses. The image intensifier component is more complicated, and therefore, warrants some elaboration. The intensifier section consists of a photocathode, a MicroChannel Plate (MCP), a phosphor screen, and a power supply (Figure 1). The photocathode receives the light photons from the night image (e.g., ambient illumination from the moon, stars, and ground lights) projected through the objective lens. Each photon striking the front of the photocathode, releases a corresponding photoelectron on the reverse side. These photoelectrons enter the MCP where "intensification" occurs.

Within the MCP, the intensification of each photoelectron produces on the order of 10^2-10^8 secondary electrons. The MCP is composed of millions of channel multipliers formed by stretching and fusing optical fibers to form the MCP. Each channel multiplier is a hollow glass tube with a lead coating on the inside surface. By introducing a current to this coating, the channel achieves the function of multiplying each photoelectron (Figure 2). The numerous electrons emerging at the exit end of the MCP

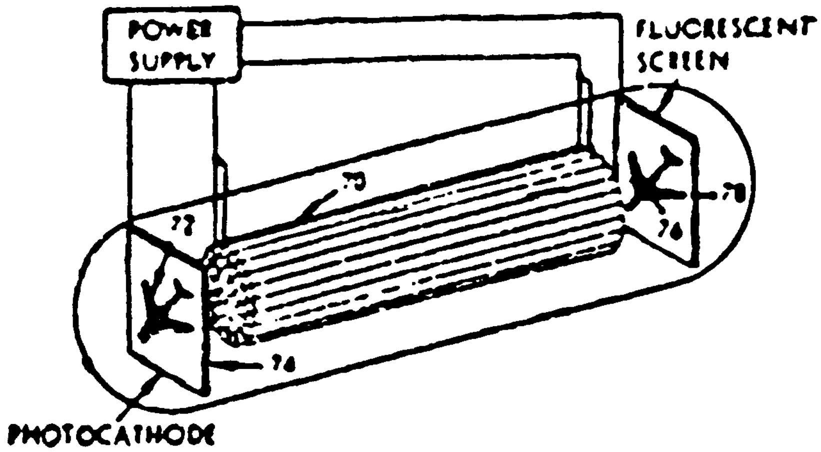

Figure 1. NVG intensifier tube schematic (Biberman and Alluisi, 1992).

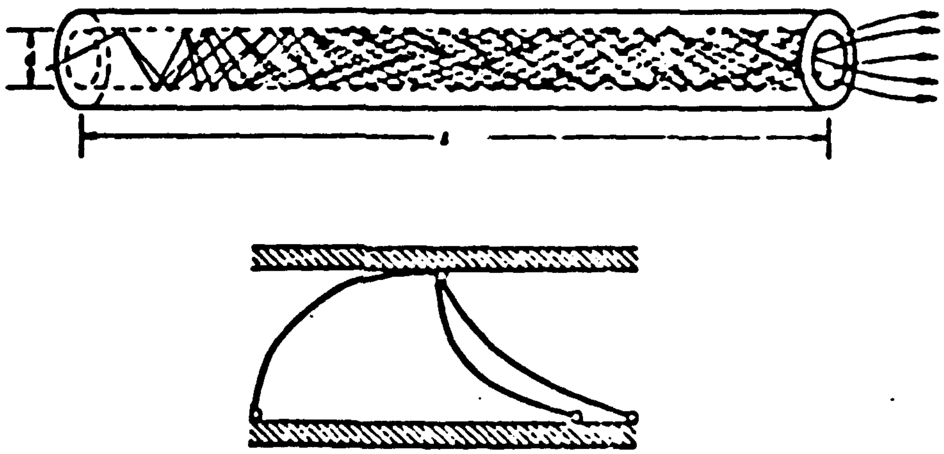

Figure 2. A channel multiplier and electron trajectories (Biberman and Alluisi, 1992).

are projected onto a phosphor screen, creating a monochrome image to be viewed through the eyepiece.

The third generation intensifiers can provide a luminance gain on the order of 2000 footlamberts per footlambert. While this is a significant technological achievement, it does not come close to presenting the viewer with a "daytime" scene. At best, NVGs provide 20/40 visual acuity.

Other limiting factors of NVGs are: field of view, resolution, and noise. Field of view currently is limited to 40° in the AN/AVS-6 (ANVIS) system. Resolution is limited primarily as a function of the number of channel multipliers in the MCP, and currently, it is 0.76 cycles per milliradian (minimum) in the ANVIS devices. Noise is present in the form of image noise that has been intensified, as well as goggle induced noise, primarily dynamic "sparkle" type noise resulting from stray electrons randomly striking the photocathode. These limitations in the visual display are most important to consider when assessing the NVG images for primary flight information.

A significant issue in NVG use is that of binocular depth perception. Wiley (1989) found a significant difference in stereopsis thresholds between the binocular unaided viewing condition and the binocular aided (AN/PVS-5 goggles) condition. This is a notable finding since binocular viewing systems and unaided binocular vision both provide stereoscopic cues (retinal disparity). This apparent loss of binocular depth cues could be responsible for pilots misjudging distances and rates of closure, resulting in "crew error" type accidents.

The purpose of this study was to:

(1) investigate the effects of modern NVGs on binocular depth perception at various levels of illumination,

(2) determine if scene contrast ratio affects binocular depth perception through the NVGs, and

(3) determine if visual noise or limited resolution are contributing factors to a loss of binocular depth cues.

LITERATURE REVIEW

To date, little research literature exists on how image noise or resolution may interfere with stereoscopic vision. Classical depth perception studies do explain some of the limitations of stereopsis in terms of illumination and contrast. More recent research has investigated the limitations of NVGs in terms of visual acuity and stereopsis. While the loss of stereopsis with NVGs has been documented, little work has been done to understand the underlying cause of this phenomenon. The technical literature relevant to these issues is discussed below.

Depth perception

Graham (1965) discusses visual space perception in terms of monocular and binocular cues. The important monocular cues are relative size, interposition, linear perspective, aerial perspective, monocular movement parallax, light and shade, and accommodation. The important binocular cues are convergence and stereopsis vision. Convergence is only effective for objects within six feet, making stereopsis the primary binocular cue for distant objects.

Stereoscopic vision occurs when the retinal image in the right eye is different than the image in the left eye when an object is viewed in space. "Theoretically, the essential stimulus condition for stereoscopic vision is a difference in convergence angles between (a) lines of sight from the two eyes that converge at a fixated object point and (b) those that converge at another object point (Graham, 1965, p.505)." The resulting retinal disparity is responsible for stereoscopic vision. Graham determined that stereoscopic vision is effective up to 495 yards.

Effects of Illuminance and Contrast on Stereoscopic Vision

Mueller and Lloyd (1948) investigated the effects of illuminance on stereoscopic thresholds. A stereoscope was used at illumination levels from the scotopic to the photopic visual range. Stereoscopic acuity as a function of illumination was found to have a relationship somewhat similar to the cone and rod components of the dark adaptation curve (Figure 3). Stereoscopic acuity decreases as illumination is reduced within the photopic range. Stereoscopic acuity remains nearly constant over the lower portion of the photopic range. Within the scotopic range of vision, stereopsis is maintained but it is severely diminished relative to that in the photopic range.

Graham (1965) cited studies by Berry, Riggs, and Duncan (1950) and Ludvigh (1947) that produced similar results

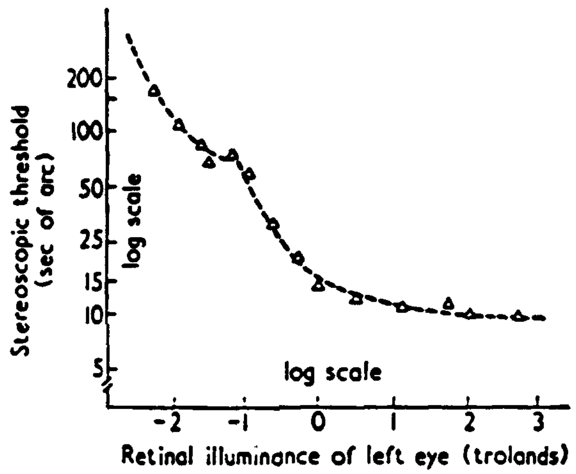

Figure 3. Relationship between stereoscopic thresholds and retinal illuminance (Ogle, 1962).

using actual objects in space. A Howard-Dolman apparatus was used in these experiments. This apparatus consists of two rods, one fixed and one that can be moved in a range fore and aft of the fixated rod. The apparatus is backlit and shielded to reduce other depth cues. Depth thresholds were the difference in rod distance that could be discriminated 75 percent of the time. The results of these experiments matched Mueller and Lloyd's results, thereby confirming that stereoscopic vision is diminished with decreasing luminance.

Richards and Foley (1974) conducted research to determine the effects of luminance and contrast on the stereoscopic processing of large disparities. A stereoscopic presentation was devised with two bars that could be varied in horizontal separation. The bars were presented with an angular separation of $1/2^{\circ}$, 1°, 2°, and 4°. Both luminance and contrast were varied for each separation. Richards and Foley found that for small angular separation (i.e., $1/2^{\circ}$) stereoscopic acuity diminished as luminance and contrast were reduced. However, fairly low levels of luminance or contrast were actually found to increase stereoacuity for large angular separations (4°).

Ogle and Weil (1958) investigated the effects of contrast on stereoscopic vision. Their subjects maintained a fixed level of light adaptation while viewing stereoscopic targets that varied in luminance by filters. The varying contrast levels were found to have no significant effect on stereoscopic vision.

Halpern and Blake (1988) also performed an experiment to examine the effect of contrast on stereoacuity. Their targets had luminance profiles matching the tenth derivative of a Gaussian function (D10). These patterns have the advantage of being limited in spatial frequency (previous researchers used targets that were complex in spatial frequency). Stereoacuity was measured at six levels of contrast. Three subjects were required to manipulate a computer generated D10 until it fell within the reference plane. Their results indicate that increased contrast greatly enhances stereoscopic acuity (Figure 4). Previous studies of a similar nature by Legge and Gu (unpublished manuscript), Heckmann, Schor, and Taylor (1987), and Campbell, Bishop, and Wright (unpublished manuscript) show the same relationship between contrast and stereoscopic vision (as cited by Halpern and Blake, 1988).

NVG Limitations

Extensive laboratory and field studies have verified that the NVGs have many limitations in representing the visual environment. Kaiser and Foyle (1991) discuss many of the human factors concerns in NVG use. The differences between natural vision and vision through NVGs include: monochromatic images, poorer resolution, smaller field of

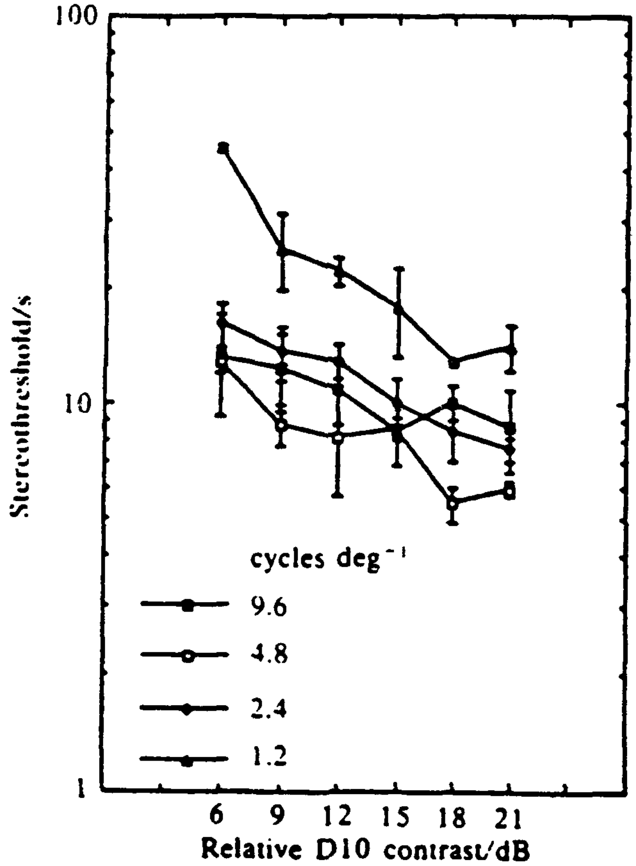

Figure 4. Stereothresholds obtained as a function of changes in binocular D10 contrast (Halpern and Blake, 1988).

view (FOV), different spectral sensitivities than natural vision, introduction of dynamic noise, and reduced contrast. In summarizing operational data, it was found that the most commonly reported static illusion with NVGs was misjudgement of height above terrain. The authors proposed four possible causes for faulty distance judgements: 1) misaccommodation resulting in blurred images, 2) framing due to restricted FOV affecting perceived object size, 3) lower resolution creating a loss of texture gradients, and 4) spectral properties causing distant objects to appear very bright resulting in distance underestimation.

A study was conducted by Kaiser and Foyle (1991) to address the FOV issue. Subjects viewed targets 20 to 100 feet away and were asked to estimate absolute distance under varying conditions. The conditions tested were day-unaided, day-unaided restricted (40^{o} FOV), night-unaided, and night-unaided restricted. No significant effect was found for FOV. Day conditions were more accurate than night conditions as the authors expected. The authors hypothesized that the reduced resolution under night conditions was responsible for less accurate distance estimations.

NVG Noise and Visual Acuity

Riegler, Whitely, Task, and Schueren (1991) conducted a study to examine the effect of signal-to-noise ratio on visual acuity. The equipment used in their experiment included a movable seat for the subjects, a moonlight simulator mounted on a tripod to simulate the moon's spectral characteristics, a Landolt C chart to assess visual acuity, a photometer to measure luminance levels, and four pairs of ITT AN/PVS-7 NVGs with different signal-to-noise ratios (SNR). Visual acuity was assessed on two levels of contrast, 20 and 95 percent. Modulation contrast (C) was calculated with the following equation:

$$C = \frac{\text{Background luminance} - \text{Target luminance}}{\text{Background luminance} + \text{Target luminance}}$$

Acuity also was assessed at two levels of illumination. Full moon illumination was defined as 0.0235 footcandles. Illumination corresponding to 0.25 moon (0.00588 footcandles) and starlight (0.01 moon, 0.000235 footcandles) were used in the experiment. Acuity was measured for the four SNRs (17.92, 15.28, 13.71, and 11.37).

Twelve subjects participated in the experiment. The subject moved toward the target and stopped the chair when he could determine the orientation of all C's on the chart. The results showed a significant effect for all three independent variables: contrast, illumination, and SNR. An increase in intensifier SNR resulted in better visual acuity at quarter moon and starlight illuminations for high and low contrast targets. There was a notable trend for SNR to have a greater impact on acuity at low levels of illumination. This study revealed that SNR does impact visual acuity through NVGs and this effect becomes greatest at the lowest levels of illumination.

Visual Acuity and Depth Perception With NVGs

Wiley, Glick, Bucha, and Park (1976) investigated depth perception with NVGs. A laboratory measure of relative depth thresholds was made using a Howard-Dolman apparatus. The variable rod was remotely adjustable by the subject. Four conditions were tested: binocular (6.70 footlamberts), monocular (6.70 footlamberts), binocular/NVG (0.012 footlamberts), and monocular/NVG (0.012 footlamberts). Depth thresholds for six subjects at a viewing distance ofsix meters were determined (Table 1). The unaided binocular threshold was significantly better than the other three conditions, but no main effect was found for the NVG viewing conditions alone.

The second part of the Wiley, et al. experiment involved a field test. Large white targets were viewed at distances of 200, 500, 1000, 1500, and 2000 feet from inside a helicopter. The targets were designed to subtend a visual angle of 10 arc seconds x 30 arc seconds at all distances. Relative depth thresholds were obtained under full moon conditions for binocular NVG viewing, and under daylight

Table 1. Relative depth thresholds with Howard-Dolman apparatus (Wiley, Glick, Bucha, and Park, 1976).

	Linear Threshold (Centimeters)	Angular Threshold (Seconds of Arc)
Binocular	1.34	5.0
Monocular	5.19	19.3
Binocular/NVG	4.80	17.9
Monocular/NVG	7.04	26.2

conditions for unaided binocular and monocular viewing. The unaided binocular and monocular thresholds differed significantly only at 2000 feet. NVG thresholds were significantly different from monocular thresholds at all distances except 200 feet, and NVG thresholds were significantly different from binocular thresholds except at 200 and 500 feet (Figure 5). The authors concluded that the reduced resolution through the NVGs probably was responsible for the decrement in relative depth discrimination.

Wiley (1989) performed an experiment to evaluate both stereopsis and acuity through NVGs. The stereopsis portion was similar in nature to the previous experiment. A Howard-Dolman apparatus was used to measure relative depth thresholds for the various conditions at a distance of six meters. Linear displacements in the two rods were converted to angular measures using the following equation:

$$n = \frac{a\,(l)}{d^2} \times 206280$$

in which

n = angular threshold in seconds of arc

a = interpupillary distance

l = linear displacement of the variable rod from the fixed rod

d = observation distance

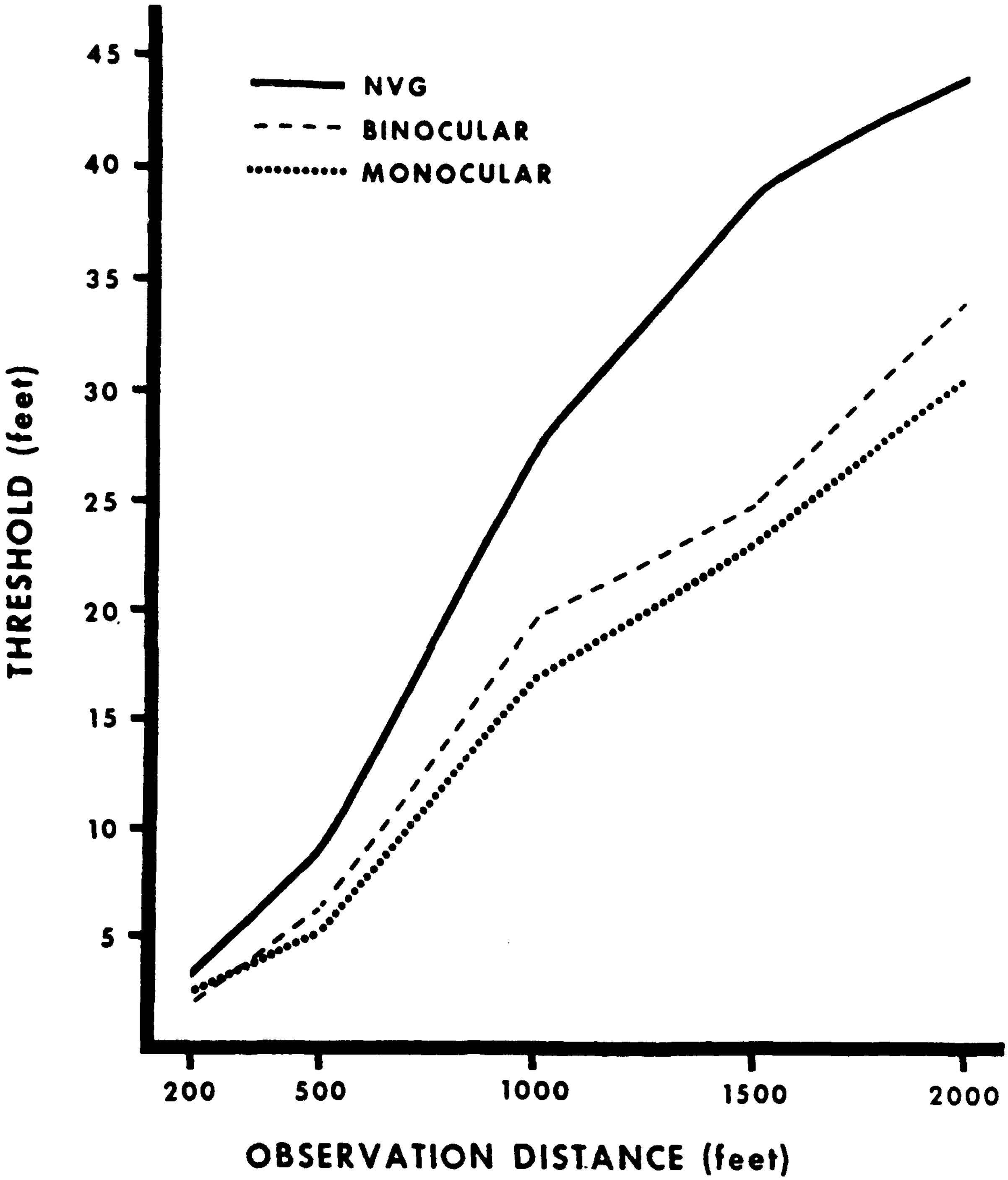

Figure 5. Linear thresholds for relative distance discrimination under three viewing conditions (Wiley et al., 1976).

Luminance of the apparatus was set at 7 footlamberts for unaided conditions, and 0.012 footlamberts for all NVG viewing conditions. The conditions tested were: unaided monocular, unaided binocular, monocular AN/PVS-5, binocular AN/PVS-5, biocular AN/PVS-7A, and biocular AN/PVS-7B. Figure 6 depicts the angular thresholds that were determined. A significant difference was found to exist between the unaided binocular condition and all other conditions.

The second part of the experiment measured the effects of contrast and luminance on visual acuity under the same six viewing conditions. The target was a Snellen optotype "E" presented for 500 msec in one of four possible orientations. The subject was required to indicate the orientation of the "E" in each trial. The "E" varied in sizes corresponding to the Snellen notations of 20/10 to 20/400, and contrast of the target was set at 94, 35, or 5 percent. Results found an acuity of around 20/50 through binocular goggles under the full moon, 94 percent contrast condition. As luminance and contrast were reduced, the visual acuity decreased. At the quarter moon, 5 percent contrast condition subjects were unable to resolve the largest target (20/400 Snellen acuity) even with NVGs. These results reveal that the luminance and contrast of the night scene greatly impact visual acuity with NVGs.

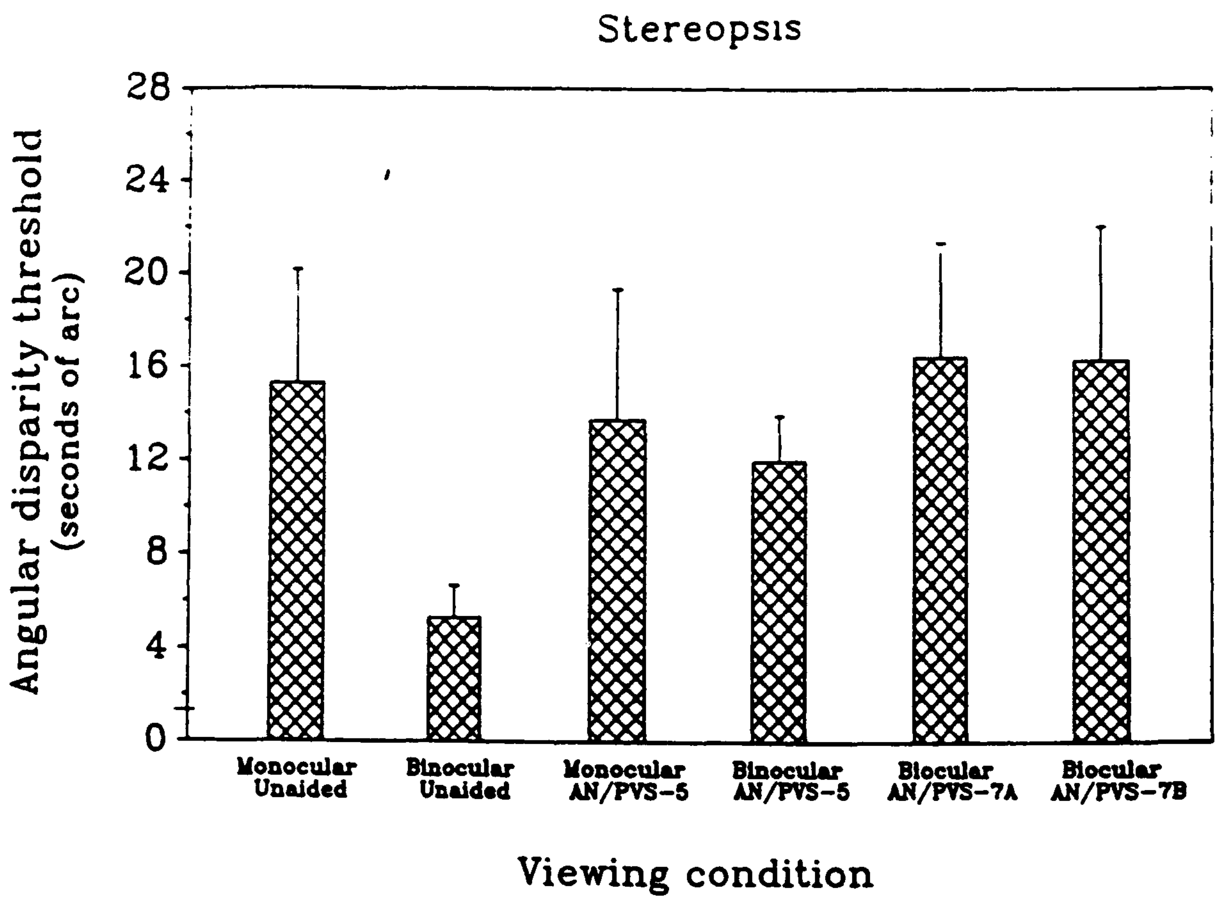

Figure 6. Stereopsis disparity thresholds for different viewing conditions (Wiley, 1989).

Summary

Graham (1965) verified that stereopsis is the only binocular depth cue useful at distances beyond a few yards and is effective up to 495 yards. Mueller and Lloyd (1948) found that luminance affects stereoscopic thresholds in much the same fashion that it affects acuity thresholds. Graham (1965) cited two additional studies that found stereoscopic thresholds increased as luminance decreased. Richards and Foley (1974) found that both diminishing luminance and contrast reduce stereoacuity for small disparities, but the reverse trend exists for large disparities. Ogle and Weil (1958) found no significant effect of contrast on stereoscopic vision. Halpern and Blake (1988) found that reduced contrast of targets limited in spatial frequency is detrimental to stereoacuity. They cited three additional studies that produced similar results. The literature reveals that while the true effects of stereoacuity may depend on the type of target being used, reduced contrast and luminance generally diminish stereoacuity.

Kaiser and Foyle (1991) discussed many of the human factors concerns with NVGs and specifically addressed the limited FOV. They found that a framing effect causing poor distance estimation did not exist. Riegler et al. (1991) investigated the impact of signal-to-noise ratio on visual acuity through NVGs. They found that SNR significantly impacted visual acuity. Wiley et al. (1976) and Wiley

(1989) found that depth perception through NVGs was significantly diminished when compared to unaided binocular viewing. Wiley (1989) found that visual acuity through NVGs was significantly diminished as luminance and contrast were reduced. This literature reveals the limitations of NVGs. Illumination, contrast, and SNR all impact the acuity through the goggles. Several studies verify the reduced stereoacuity when viewing through NVGs.

While the research to date has shown a loss of depth perception through NVGs, no studies have looked at the effects contrast, scene illumination, or SNR have on stereopsis with NVGs. Since these factors have been found to impact acuity, it is likely that similar results could be found for stereopsis. The purpose of this study was to investigate the effects that different conditions of contrast and illuminance have on stereopsis when viewing through NVGs. This study may better delineate the limitations of NVGs as well as provide some insight into the impact resolution and noise have on stereopsis through NVGs.

METHOD

In this experiment subjects performed a relative depth test designed to isolate stereopsis. Subjects manipulated a modified Howard-Dolman apparatus under varying levels of illumination and contrast. Subjects performed the depth judgments under unaided binocular conditions and while wearing ITT AN/AVS-6 (ANVIS) binocular NVGs.

Subjects

Ten male and two female volunteers participated in the experiment (18 to 28 years of age). Each participant was screened for far distance visual acuity and stereoacuity using a Bausch and Lomb Ortho-Rater. Participants were required to meet a minimum criterion of 20/25 Snellen acuity (corrected or uncorrected) and at least marginal stereoacuity (top two lines on test screen).

Equipment

The Howard-Dolman apparatus was modified to allow for contrast and luminance manipulation. The apparatus itself consisted of two bars mounted three inches apart horizontally (center to center) with the left bar being fixed and the right bar capable of moving 50 centimeters fore and aft of the fixed bar via a string. The bars of the apparatus were replaced by flat targets made of exposed photographic paper. Three pairs of bars were used of differing exposure to provide three distinct contrasts. Each set of targets was cut from the same piece of photographic paper to ensure equivalent gray shades. A white background was placed approximately five feet behind the targets. This arrangement provided the luminance modulation contrasts of 83 percent, 53 percent, and 24 percent. All contrast conditions were measured with a Minolta CS-100 photometer.

The apparatus was illuminated from a single calibrated light source under night conditions, and three 150 watt flood lamps under the day condition. The light sources were located approximately three feet above and 12 feet in front of the apparatus. Neutral density filters were used to manipulate the illumination, thus maintaining a constant color temperature throughout all conditions. All illuminance measures were performed using a Minolta T-1 illuminance meter. The entire apparatus was shielded to eliminate shadows and other non-stereoscopic cues. A screen was placed between the apparatus and subject between trials.

Participants were seated six meters from the targets. The targets were viewed through one of two devices. Under daylight conditions, a pair of PVC pipes (2.5 inches in diameter and three inches in length) were used to simulate a binocular viewing device. These pipes held neutral density filters on the end to allow manipulation of daylight scene illumination. For nighttime viewing, ITT AN/AVS-6 goggles were used. Illumination under nighttime conditions was manipulated at the light source using neutral density filters. Both binocular viewing devices were hard mounted in front of the subject. The NVGs were adjusted for each subject following the operator's manual provided with the goggles, and each tube was focused on the stationary target of the Howard-Dolman apparatus by the subject.

Testing Method

The relative depth threshold task required the participant to view the Howard-Dolman apparatus and adjust the right target ("rod") until it appeared to be in the same plane as the left stationary target ("rod"). When the participant judged the targets to be equidistant, a measure of the linear error in the positioning of the target was taken to estimate the stereoscopic threshold. The starting position of the right target for each trial fell randomly into any one of ten locations fore or aft of the stationary target (+ or - 1 through 10 centimeters).

After passing the vision test, participants received instructions on how to manipulate the Howard-Dolman apparatus and to adjust the NVGs for correct focus and interpupillary distance. A practice session preceded experimental trials, which consisted of the subject performing the task four times without the goggles and four times with the goggles. Then, final instructions and clarifications were provided to the participant prior to beginning experimentation.

In the experimental session, the participant performed the same task as in practice for each viewing condition. Once the right target was in starting position, the screen was removed to reveal the two targets. The participant manipulated the right target by means of a string until it appeared aligned in depth with the left target. At this point, the screen was placed in front of the apparatus while the experimenter recorded linear error and set the apparatus for the next trial. This procedure was repeated six times for each viewing condition.

Experimental Design

This study employed a 4 x 3 x 2, within-subjects design. The viewing conditions were blocked so that subjects received all illumination and contrast levels for the first viewing condition (day or night) before receiving the second viewing condition. Viewing condition and illumination were counterbalanced to eliminate presentation order effects. Contrast was blocked within each illumination condition so that all contrast levels were tested at a given illumination level before moving to the next level of illumination. Contrast was presented randomly within each level of illumination. The experiment was completed in a single session for each participant.

Dependent variables. Linear error in centimeters (distance between targets) was recorded on each trial. These measures were averaged over replications for the final analysis.

Independent variables. Illumination Level (I). The illumination levels were specified as 100 percent, 50 percent, 10 percent, and 1 percent. The four night illumination conditions were based on moonlight illumination levels. These illumination levels were full moon, half moon, 0.1 moon, and 0.01 moon (starlight). Full moon illumination was defined as 0.0235 footcandles (RCA, 1974). The four nighttime illuminations were set at 0.0235, 0.01175, 0.00235, and 0.000235 footcandles. Illumination was manipulated by placing neutral density filters in front of the light source.

Daytime illuminance was set to achieve the same four percent magnitudes as presented in the nighttime conditions. The highest illumination was 79 footcandles. The four levels were achieved by placing filters over the ends of the PVC viewing device to reduce scene illumination appropriately. The four illuminations were 79, 39.5, 7.9, and .79 footcandles. The lowest daytime illuminations were important in that they produced a luminance roughly equivalent to the luminance range of the NVG phosphor screen. Subjects were allowed four minutes to accommodate to each level of illumination prior to testing.

Target Contrast (C). Contrast was manipulated across three levels: high, medium, and low. The calculated positive target-to-background contrasts were 83, 53, and 25 percent. A fourth target with a 2 percent contrast was dropped from the experiment when pilot testing revealed the target was not visible through the NVGs. The modulation contrast was calculated from the following equation:

$$C = \frac{\text{Background luminance} - \text{Target luminance}}{\text{Background luminance} + \text{Target luminance}}$$

As previously, mentioned a white background was used throughout the study. Contrast was manipulated by changing the gray shades of the target pairs. No colors were used to maintain the monochrome nature of NVG images during unaided viewing.

Viewing Condition (V). The subjects performed the task under two viewing conditions, nighttime aided and daytime unaided. The aided viewing condition consisted of binocular viewing of the nighttime scenes through the ANVIS goggles.

The unaided viewing condition consisted of binocular viewing of the daytime scenes through a pair of 2 1/2 inch PVC pipes with the naked eye.

Analysis

The dependent variable of linear error was analyzed using Analysis of Variance (ANOVA) procedures. Appropriate post hoc comparisons were used to investigate all significant main effects found in the ANOVA.

Additional analysis included the measurements of signal-to-noise ratio and resolution of the NVGs at the illumination levels tested. This was done utilizing NVG SNR measuring equipment as well as a Hoffman Test Bench. The noise measurements were electronically measured at a specific illumination and calculations were used to determine noise as a function of illumination. Resolution was measured using a standard Air Force resolution target projected at a calibrated illumination by the Hoffman Test Bench onto the photocathode of the intensifier tube. Correlational techniques were utilized to investigate the relationship between stereoscopic vision and the resolution and signal-to-noise ratio of NVGs.

RESULTS

The 4 x 3 x 2 within-subjects design was analyzed using standard ANOVA procedures. The first part of the results section presents all statistical analyses of the data from the experimental design. The second part shows resolution measurements and analyses for the NVGs.

The Greenhouse-Geiser correction for homogeneity of covariance was employed in the ANOVA. Under the homogeneity of covariance assumption, the variance for each individual's scores is assumed to be equivalent for all participants in a repeated measures design. This is rarely the case and if not dealt with creates a positive bias in the analysis. The Greenhouse-Geiser correction evaluates the F-ratios against new critical values allowing for maximum heterogeneity. Epsilon values (E) used in the Greenhouse-Geiser correction are shown where appropriate. Post hoc analyses were performed using Newman-Keuls Sequential Range Tests where necessary. Table 2 shows the ANOVA employed for the study.

Viewing Condition. The main effect of viewing condition (V) was statistically significant ($F = 40.43$, $p < 0.0001$, $E = 1.0$). This main effect is shown in Figure 7. The mean error under daylight conditions was 3.592

Table 2. ANOVA summary table for experimental data.

ANOVA Summary Table:

SOURCE	DF	SS	MS	F	P_{G-G}
Between					
S(Subject)	11	951.25	86.48		
Within					
V(view cond)	1	1086.40	1086.40	40.43	<.0001
VxS	11	295.55	26.87		
I(illumination)	3	44.40	14.80	1.91	.1569
IxS	33	255.46	7.74		
C(contrast)	2	30.10	15.05	5.17	.0197
CxS	22	64.02	2.91		
IxV	3	51.06	17.02	2.27	.1040
IxVxS	33	247.09	7.49		
CxV	2	2.40	1.20	0.20	.7854
CxVxS	22	131.02	5.96		
IxC	6	28.24	4.71	0.77	.5195
IxCxS	66	403.63	6.12		
IxCxV	6	43.79	7.30	0.96	.4258
IxVxCxS	66	501.66	7.60		
Total	287	4136.07	1297.65		

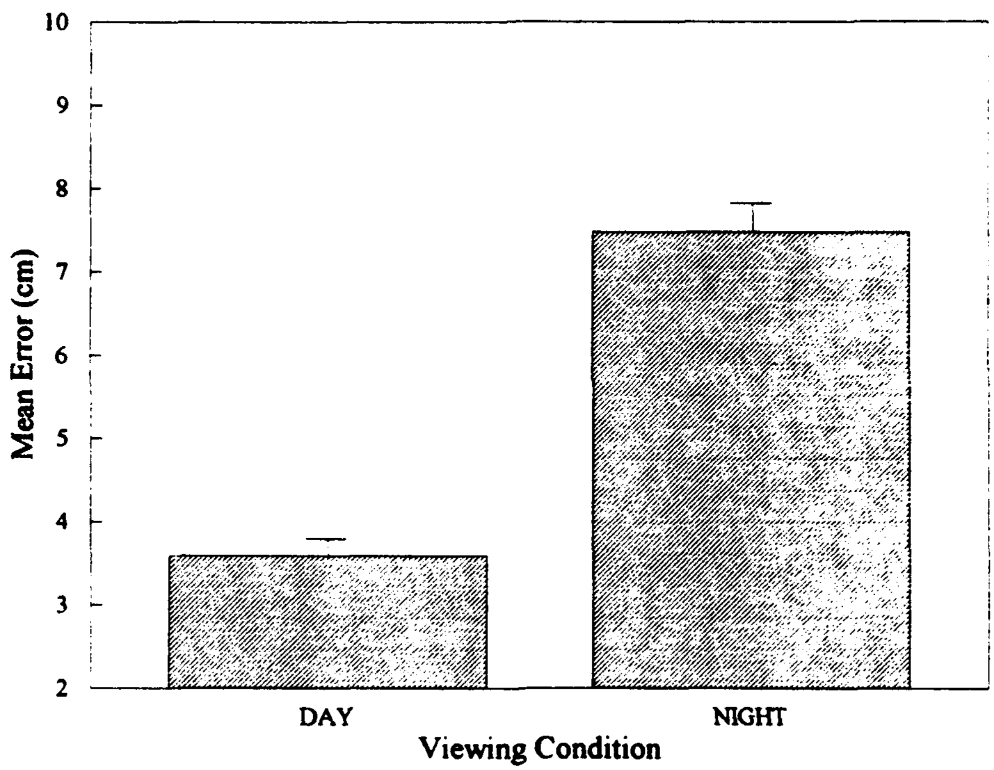

Figure 7. Viewing condition effect with standard error bars.

centimeters, while mean error under NVG conditions was 7.477 centimeters. Depth judgment with the NVGs was degraded by 108 percent in comparison to the daylight viewing condition.

Contrast. The main effect contrast (C) also was significant (F = 5.171, p = 0.0197, E = 0.859), and it is shown in Figure 8. Post hoc analysis using the Newman-Keuls method revealed no significant differences among the three contrast levels. A simple F-test pairwise comparison of arithmetic means, known as the Least Squares Means (LSM) method, was employed to try and further analyze the contrast effect. This method is not a statistically sound procedure due to multiple comparisons of means, but it is a useful tool for post hoc analysis when normal post hoc procedures are not sensitive enough to reveal significant differences. Reported P-values for the Least Squares Means analysis above 0.05 should be accepted with caution due to the multiple comparisons which tend to inflate Type 1 error.

The LSM test found that the low (25 percent) contrast condition resulted in significantly worse performance than the medium (53 percent) contrast condition (t = -2.626, p = 0.0154) and the high (83 percent) contrast condition (t = -2.921, p = 0.0079). The mean error in performing the depth test was 5.270 cm for 83 percent, 5.343 cm for 53 percent, and 5.990 cm for 25 percent. Depth performance under the low contrast condition was degraded by 12 percent in

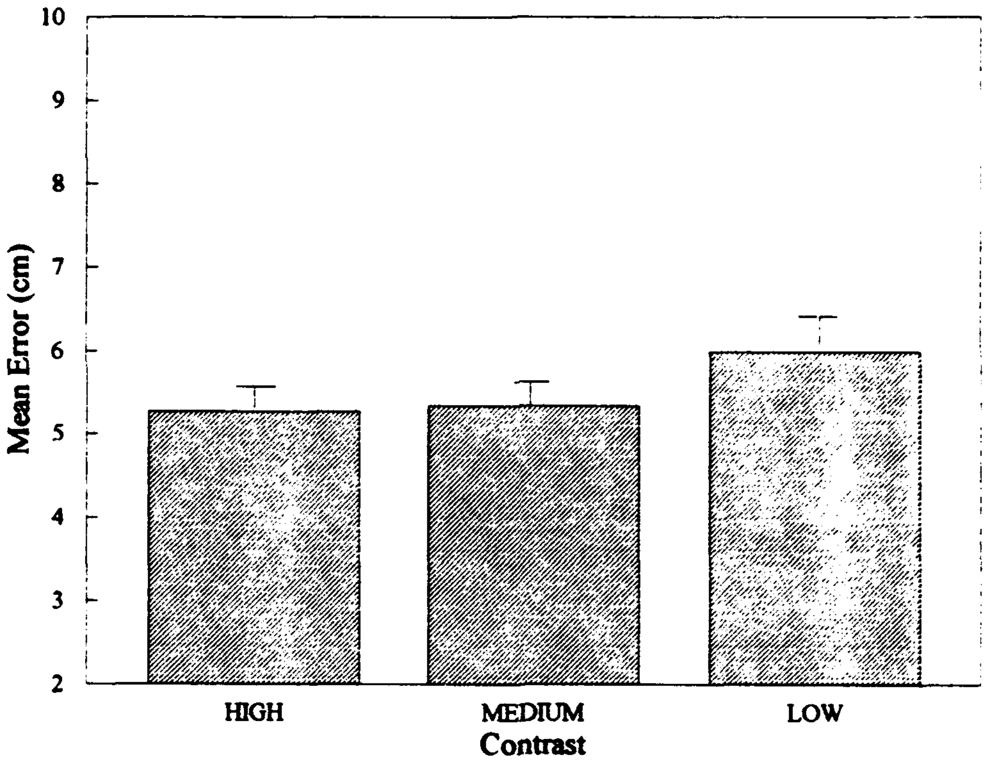

Figure 8. Contrast effect with standard error bars.

comparison to the medium contrast and by 14 percent in comparison to the high contrast level.

Illumination x Viewing Condition. Although the main effect illumination was not statistically significant, the interaction between illumination and viewing condition was significant ($F = 2.27$, $p = 0.104$, $E = 0.926$). Figure 9 presents the illumination by viewing condition interaction. The Newman-Keuls analysis did not detect any significant effects within each viewing condition, but the LSM pairwise comparisons revealed that under daylight conditions, illumination had no significant effect ($p < 0.05$); but, under NVG conditions, illumination did have a significant effect. The mean error for each night illumination was 8.064 cm for 100 percent, 8.326 cm for 50 percent, 6.442 cm for 10 percent, and 7.074 cm for 1 percent. Error under the 10 percent illumination was significantly less than both the 100 percent illumination ($t = 2.514$, $p = 0.017$) and the 50 percent illumination ($t = 2.921$, $p = 0.0063$). Error under the 50 percent illumination was significantly higher than the 1 percent illumination ($t = 1.941$, $p = 0.0609$). Another important result is the significantly higher error for all NVG illuminations when compared to the lowest daytime illumination using the Newman-Keuls analysis (all $p < 0.05$).

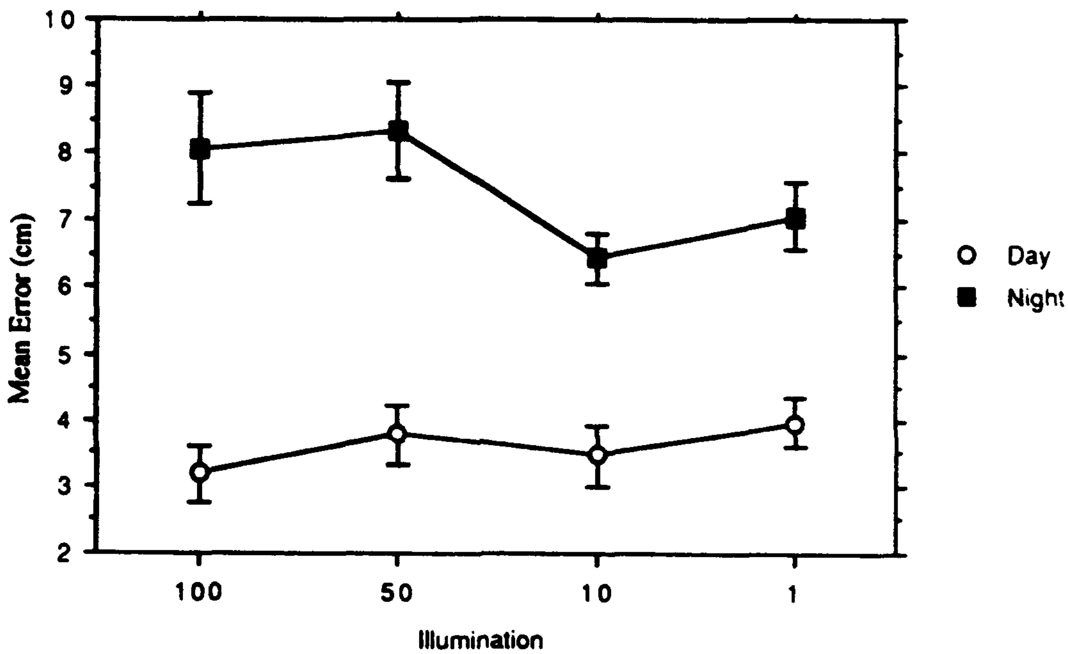

Figure 9. Illumination x viewing condition interaction with standard error bars.

Resolution and SNR Analyses

Resolution and SNR were approached in two ways. The first method used theoretical calculations to model resolution/SNR as a function of illumination (ITT, 1993). Resolution calculations and measurements are presented in Appendix D. The best resolution designed into the goggles is assumed to be 40 line pairs per millimeter (LP/mm). If noise was not factored into the resolution, then resolution would theoretically remain at 40 LP/mm throughout the illuminations of interest. However, as illumination decreases, the gain of the goggles increases. This results in more electronic noise, subsequently reducing the SNR. The resolution function is adjusted accordingly to reflect the reduced SNR as illumination is reduced. The resulting function (Figure 10) shows a relatively constant resolution at the higher illuminations with a drop in resolution beginning somewhere around 0.01 fC as a result of the decreasing SNR. At an illumination of 0.000012 fC, the resolution is diminished to 10.8 LP/mm.

The second approach utilized the actual measurement of resolution on the Hoffman Test Bench. Illuminations from 0.048 fC down to 0.000012 fC were tested. Resolution was determined for each of the intensifier tubes that comprised the ANVIS set used in the experiment. The resolution was averaged to get an estimate of system resolution for the image intensifier portion of the NVGs. The resulting

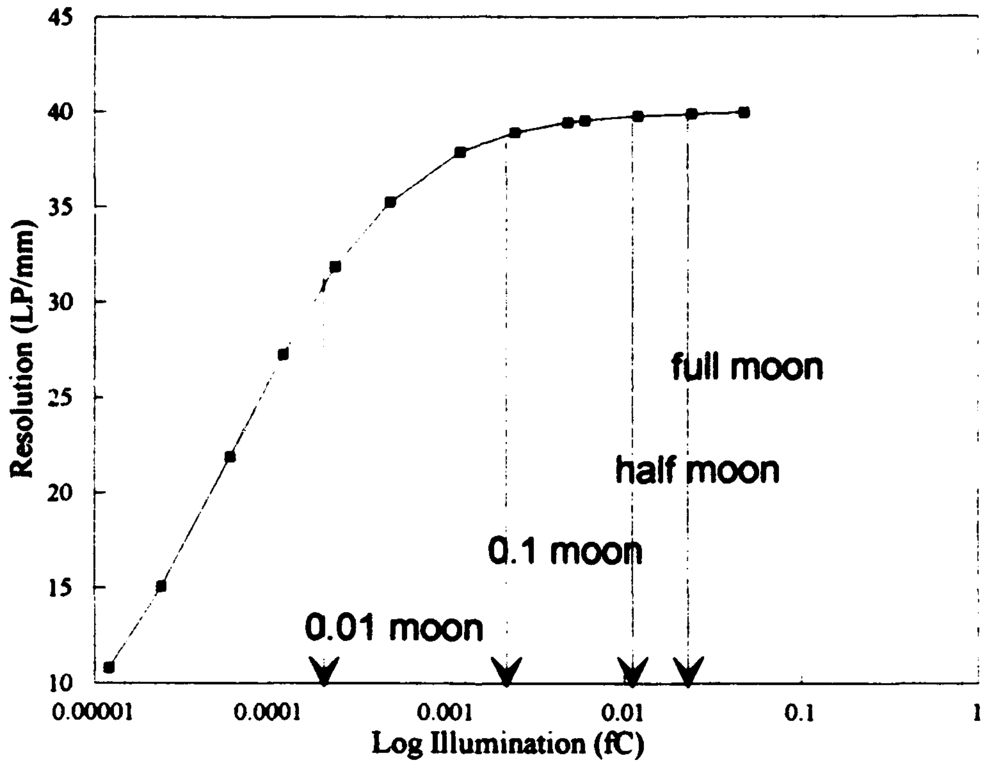

Figure 10. Calculated (theoretical) resolution vs. log illumination.

resolution function (Figure 11) nearly matches the theoretical function at the lower illuminations.

An important difference is evident at the higher illuminations. It is evident that resolution is diminished somewhere above 0.0048 fC. The diminished resolution at higher illuminations is not accounted for in the theoretical model, as is evident when the two graphs are presented together as in Figure 11. At 0.048 fC, the measured resolution is only 32.2 LP/mm, which is far below both the theoretical resolution of 40 LP/mm at this illumination and the maximum measured resolution of 38.1 LP/mm in the 0.0024 fC to .0048 fC range.

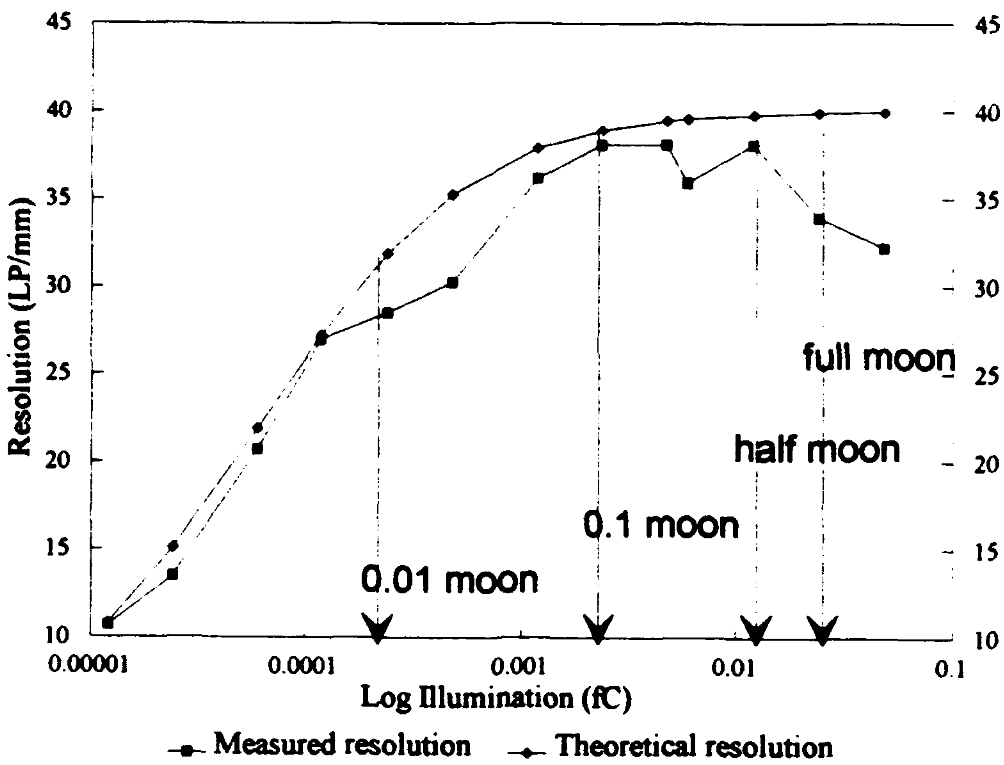

Figure 11. NVG resolution vs. illumination (theoretical and measured).

DISCUSSION

Analysis of Variance

Most of the results of the ANOVA were expected based on the previously discussed literature. The significant loss of stereoacuity with the NVGs was reconfirmed by the significant effect of viewing condition. The significance of contrast also was expected, although the fact that it took a fairly low contrast to show a decrease in stereoacuity was interesting. This result indicates that stereoacuity remains fairly constant over a wide range of contrast levels. The effect of illumination was not significant, which is most likely a result of the relatively constant stereoacuity under daylight conditions. Based on the assumption that the stereopsis function under NVG conditions is different than under unaided conditions, the illumination x viewing condition interaction was expected.

Viewing Condition. The significant difference in stereoacuity between the binocular daylight viewing and the binocular NVG condition follows results from previous research (Wiley et al., 1976; Wiley, 1989). Considering theresear binocular nature of both conditions, it is apparent that there is something in the ANVIS goggles that is interfering with stereoscopic vision. A loss of some monocular cues is likely to reduce some depth perception; however, there is little evidence to support this contention since unaided monocular viewing conditions were not found to be significantly different from monocular NVG conditions (Wiley, 1989). Previous studies have suggested that the loss of stereopsis when operating with NVGs is probably due to the reduced resolution when viewing scenes through the goggles (Wiley et al., 1976 ; Wiley, 1989). Resolution is likely to be a factor in the overall loss of stereoacuity. Wiley (1989) linked the loss of stereoscopic vision under unaided nighttime conditions to the reduction in scene resolution at night. This would lead to the conclusion that degraded NVG resolution may be the primary factor for the diminished stereoacuity during NVG use.

Considering the degree of stereoscopic degradation (over a 100 percent increase in error) with NVGs, under the relatively high resolution the manufacturers have achieved (as high as 40 LP/mm), it is likely that other factors are involved in the loss of stereoacuity. One factor that must be considered is the noise in the NVG image. Image noise likely has a role in reducing the stereoacuity during NVG use. The impact of noise cannot be fully understood from this research but further discussion below will reveal some of the possible links.

Contrast. The significance of contrast on stereoscopic vision has not been widely agreed upon (Halpern and Blake, 1988; Ogle and Weil, 1958; Richards and Foley, 1974). Most vision research confirms that better visual performance is achieved under high contrast conditions as opposed to low contrast conditions. This study confirmed that stereoacuity is in fact diminished by low contrast conditions. It is difficult to hypothesize what element of the visual system drives this effect. Perhaps the easiest explanation, where stereopsis is concerned, is that higher contrast allows the eye to obtain a better fix on a given target, which in turn will allow for better stereoacuity, due to more precise viewing angles for each eye. Of course, for the purpose of this study, it is more important to know that contrast does impact stereoacuity.

An important element of the contrast effect found in this study is the difference between the day and NVG conditions (Figure 12). Under daylight conditions, as contrast decreased, error increased in a relatively linear fashion. Under the NVG condition, contrast did have a somewhat different, though not significant, effect on stereoacuity. As contrast decreased, the error increased; however, a larger increase in error occurred when moving from the 53 percent to 25 percent contrast condition. This high error under the NVG, 25 percent contrast condition is the primary reason that contrast was a significant main

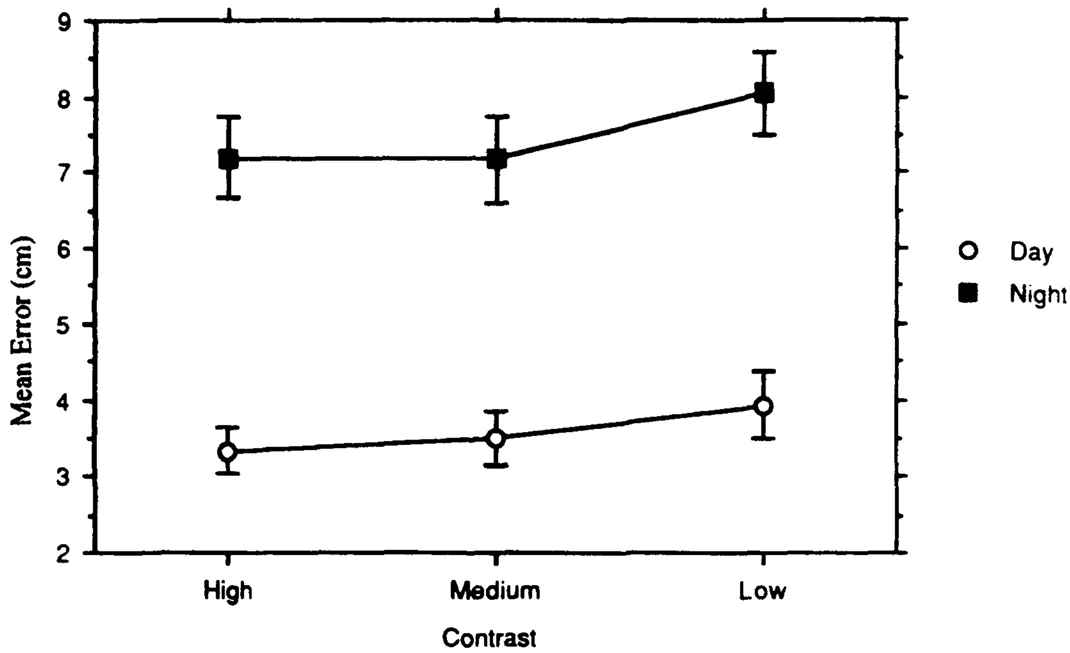

Figure 12. Contrast x Viewing Condition interaction.

effect. The results support the statement that low contrast (less than 50 percent) will diminish stereoacuity regardless of the viewing condition. It must be pointed out that the results also indicate that contrast is likely to have a greater impact on NVG viewing. It is likely that scene contrasts below 50 percent will diminish stereoacuity to a greater degree under NVG conditions when compared to normal unaided viewing conditions. This is a significant finding considering the operational environment under which NVGs are used. Tjernstrom (1992) determined that most scenes where helicopters operate rarely exceed a modular contrast of 50 percent. Therefore, contrast becomes an important consideration for both the designers and users of NVGs.

Illumination x Viewing Condition. The results for this interaction are somewhat difficult to explain. This interaction perhaps holds the key to explaining what aspect of NVGs is reducing stereoacuity. The results show that the effects of illumination on stereoacuity are very different when NVGs are used. The illuminations under the daytime condition had a relatively small effect on stereoacuity, with only a minimal trend for reduced illumination to reduce stereoacuity. Illumination had a much different effect on stereoacuity under the NVG condition. At full moon and half moon illuminations, error was relatively constant and significantly higher than the 10 percent moon condition.

Error was significantly lower at the 1 percent moon (starlight) condition when compared to the 50 percent condition. It can be said from these data that the best stereoacuity with NVGs is achieved somewhere between starlight and half moon conditions.

It was somewhat unexpected that the full moon and half moon conditions would result in the worst stereoacuity. This has important implications for NVG operations, when they are being used under conditions where scene illumination exceeds 0.012 fC. Subject observations did reveal that halo and blooming effects were more apparent at the two highest levels of illumination. They also observed that the images appeared somewhat washed out in comparison to the two lower illuminations. Individuals who have used NVGs in actual flight operations have pointed out that the 25 to 50 percent moon nights generally give them the most preferred image for flying. These subjective comments taken with the empirical data reveal a serious limitation in NVGs that should be addressed. The results of this research would indicate that NVGs are most effective, where stereoscopic vision is concerned, in the 0.012 fC to 0.00024 fC range, and above and below these levels of illumination there are factors involved which diminish stereopsis.

One item of interest that this interaction revealed is that even the lowest daylight illumination resulted in significantly better stereoacuity than all of the NVG conditions. This is important because the scene luminance of the 0.79 fC daylight condition was roughly the equivalent of the scene luminance displayed by the goggles (around 1 cd/m^2). Since luminance was nearly equal, but stereoacuity was not, this rules out the low luminance level of the NVG display as having a significant impact on stereoacuity.

Resolution/SNR. The results of the resolution measurements were as expected. It is important to note that the theoretical model of resolution/SNR does not account for the reduced resolution at high illuminations due to the fact that this phenomenon is not clearly understood at this time. Depending on the system, resolution is highest around 0.0048 to 0.0024 fC. It remains fairly constant in this region but drops on both ends. As illumination is reduced below 0.0024 fC, the shrinking SNR is considered the primary factor in reducing illumination. Therefore, it can be concluded that it is a worthwhile effort to attempt to increase SNR at the lower illuminations.

As illumination increases above 0.0048 fC, resolution begins to drop off. This phenomenon has several possible explanations, but it essentially is due to the fact that the image intensifiers simply were not designed to handle the higher illuminations. It is likely that the 'halo' and 'blooming' effects caused by bright lights and reflections begin to impact resolution at these light levels, even though they may not be detectable to the observer. There is also an apparent 'washing out' of the image at the highest light levels. This has the same effect as reducing contrast. These factors, as well as other imperfections, appear to have an increasing impact on resolution as illumination increases. Design limitations of the photocathode, MCP, and the phosphor screen could also result in a type of overload that causes increasing error in the display of the image. Regardless of the cause, this is an issue of some concern and should be addressed by both the designers of the NVGs and the users of the NVGs.

CONCLUSION

The results of this study confirm the fact that stereoscopic vision is significantly reduced by NVGs. In general, some of the lost stereoacuity with NVGs can be attributed to the limited goggle resolution as compared to daylight resolution. However, the resolution of NVGs is not the only factor to impact stereopsis. This study points out other causes of this effect, such as dynamic noise, halos, blooming, and washed out images (reduced contrast).

The results of this research also confirmed the importance of contrast for stereopsis. High contrast ratios appear to be important for stereopsis regardless of the viewing condition. Contrast levels below 50 percent degrade stereoacuity significantly. This effect is more pronounced when NVGs are being used. This is an important point given the fact that most arenas of NVG operations do not exceed 50 percent contrast. Since low contrast levels cannot be avoided by the NVG users, it is important that NVG manufacturers consider ways of reducing the degree to which NVGs further reduce scene contrast and subsequently stereoacuity.

The impact of high illuminance levels on stereoacuity merits further investigation. The fact that subjects exhibited the worst stereoacuity under half moon to full moon illuminations is an important finding. The washed out image, obvious halos and blooming effects (all noise related effects), along with other undetermined effects at these higher illuminations, negatively impact stereoacuity. It is probable that these effects stem from reduced resolution and contrast, and increased noise.

While NVGs afford new operational environments for the military, there remains the need to consider the visual limitations the goggles impose on the pilots and how those limitations are affected by changes in the environment. This study found that illumination and contrast are important considerations for NVG pilotage, based on the assumption that stereoacuity is an important element for safe flight. It is evident that further development of NVGs should not only be concerned with improving resolution, but also with improving the image quality at higher illuminations as well the contrast the goggles are capable of displaying.

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APPENDIX A - Instructions to Subjects

INSTRUCTIONS TO SUBJECTS

In this experiment you will be performing a task to test your depth perception under several different conditions. Half of the trials will occur in daylight conditions, while the other half will occur in nighttime conditions using night vision goggles. If you have any questions during this session please feel free to ask.

Twenty feet in front of you is an apparatus with two bars. The left bar always stays in the same place. You control the placement of the right bar with the string in front of you. The bars are currently aligned in the same plane, so they should appear to be equidistant from you. At this time please pick up the string and get a feel for how you can move the right bar fore and aft of the left bar.

At the start of each trial the right bar will be placed randomly in one of ten positions fore or aft of the left bar. Your task is to pick up the string and adjust the right bar until it appears to be aligned with the left bar. You may take your time in aligning the bars. It is important that for each trial you line up the bars as best as you can.

The experiment will proceed as follows: The light level will be adjusted by the experimenter. You will be given a four minute period for your eyes to adjust to each light level. Prior to each trial, a screen will be placed in front of the bars while the experimenter sets the position of the right bar. When the screen is removed you are to pick up the string and move the right bar until it lines up with the left bar. When you are done, set the string down and inform the experimenter. The screen will be placed back in front of the bars while the experimenter takes measurements and sets up the next trial. Be aware that we will be testing several different light levels and the contrast of the bars will be changing throughout the experiment. Are there any questions at this time?

We will begin by practicing the procedure without the goggles. We will use the procedure I just described, and please remember to line up the targets as best you can.

Remember:

- When the screen is removed look at the bars and pick up the string

- Adjust the right bar until it is lined up with the left bar

- Set down the string and wait for the next trial

At this time we will adjust the NVGs to ensure proper alignment and focus.

We will now practice the procedure again with the night vision goggles. If at any time you have difficulty seeing through the goggles or they appear out of focus please inform the experimenter.

We are now ready to begin the experiment. We will have a short break halfway through the session.

Do you have any questions at this time?

APPENDIX B - Means Tables

Table B-1. Selected means tables for experimental data.

Means table for Viewing Condition.

	Mean	Std. Dev.	Std. Error
Day	3.592	2.572	0.214
Night	7.477	3.863	0.302

Means table for Contrast.

	Mean	Std. Dev.	Std. Error
High	5.27	3.637	0.371
Medium	5.343	3.747	0.382
Low	5.99	3.994	0.408

Means table for Viewing Condition x Illumination.

	Mean	Std. Dev.	Std. Error
Day, 100	3.183	2.459	0.41
Day, 50	3.773	2.827	0.471
Day, 10	3.454	2.722	0.454
Day, 1	3.959	2.282	0.38
Night, 100	8.064	4.897	0.816
Night, 50	8.326	4.388	0.731
Night, 10	6.442	2.275	0.379
Night, 1	7.074	3.057	0.509

Means table for Viewing Condition x Contrast.

	Mean	Std. Dev.	Std. Error
Day, High	3.339	2.159	0.312
Day, Med.	3.507	2.391	0.345
Day, Low	3.931	3.091	0.4[illegible]6
Night, High	7.202	3.803	0.54[illegible]
Night, Med.	7.18	3.971	0.573
Night, Low	8.049	3.746	0.541

APPENDIX C - Least Means Squares Tables

Table C-1. Least Means Squares tables for contrast effect.

	LSmean	Std Dev.	Std. Error
High	5.27	1.706	0.174
Medium	5.343	1.706	0.174
Low	5.99	1.706	0.174

	Vs.	diff.	Std. Error	t-Test	P-Value
High	Medium	-0.073	0.246	-0.296	0.7702
	Low	-0.719	0.246	-2.921	0.0079
Medium	Low	-0.646	0.246	-2.626	0.0154

Table C-2. Least Means Squares tables for illumination x viewing condition interaction.

	LSmean	Std. Dev.	Std. Error
Day, 100	3.183	2.736	0.456
Day, 50	3.773	2.736	0.456
Day, 10	3.454	2.736	0.456
Day, 1	3.959	2.736	0.456
Night, 100	8.064	2.736	0.456
Night, 50	8.326	2.736	0.456
Night, 10	6.442	2.736	0.456
Night, 1	7.074	2.736	0.456

	Vs	Diff.	Std. Error	t-Test	P-Value
Day, 100	Day, 50	-0.59	0.645	-0.915	0.3669
	Day, 10	-0.272	0.645	-0.422	0.676
	Day, 1	-0.777	0.645	-1.205	0.2369
	Night, 100	-4.881	0.645	-7.568	0.0001
	Night, 50	-5.144	0.645	-7.975	0.0001
	Night, 10	-3.26	0.645	-5.055	0.0001
	Night, 1	-3.892	0.645	-6.034	0.0001
Day, 50	Day, 10	0.318	0.645	0.493	0.6252
	Day, 1	-0.187	0.645	-0.29	0.7737
	Night, 100	-4.291	0.645	-6.653	0.0001
	Night, 50	-4.554	0.645	-7.06	0.0001
	Night, 10	-2.67	0.645	-4.14	0.0002
	Night, 1	-3.302	0.645	-5.12	0.0001
Day, 10	Day, 1	-0.505	0.645	-0.783	0.4392
	Night, 100	-4.609	0.645	-7.146	0.0001
	Night, 50	-4.872	0.645	-7.553	0.0001
	Night, 10	-2.988	0.645	-4.633	0.0001
	Night, 1	-3.62	0.645	-5.613	0.0001
Day, 1	Night, 100	-4.104	0.645	-6.363	0.0001
	Night, 50	-4.367	0.645	-6.77	0.0001
	Night, 10	-2.483	0.645	-3.85	0.005
	Night, 1	-3.115	0.645	-4.83	0.001
Night, 100	Night, 50	-0.262	0.645	-0.407	0.6866
	Night, 10	1.621	0.645	2.514	0.017
	Night, 1	0.989	0.645	1.534	0.1346
Night, 50	Night, 10	1.884	0.645	2.921	0.0063
	Night, 1	1.252	0.645	1.941	0.0609
Night, 10	Night, 1	-0.632	0.645	-0.98	0.3343

APPENDIX D - Resolution Calculations and Measures

Table D-1. NVG measured and calculated resolutions.

Measured Resolutions:

ILLUMINATION(fC)	TUBE 1(#37270) RESOLUTION(LP/mm)	TUBE 2(#34425) RESOLUTION(LP/mm)
0.048	35.9	28.5
0.024	35.9	32
0.012	35.9	40.3
0.006	35.9	35.9
0.0048	40.3	35.9
0.0024	40.3	35.9
0.0012	40.3	32
0.00048	32	28.5
0.00024	28.5	28.5
0.00012	28.5	25.4
0.00006	25.4	16
0.000024	14.3	12.7
0.000012	11.3	10.1

ILLUMINATION(fC)	Measured Aver. Res. (LP/mm)	Calculated Res. (LP/mm)
0.048	32.2	39.94
0.024	33.95	39.89
0.012	38.1	39.77
0.006	35.9	39.55
0.0048	38.1	39.44
0.0024	38.1	38.9
0.0012	36.15	37.88
0.00048	30.25	35.25
0.00024	28.5	31.86
0.00012	26.95	27.23
0.00006	20.7	21.88
0.000024	13.5	15.08
0.000012	10.7	10.8

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