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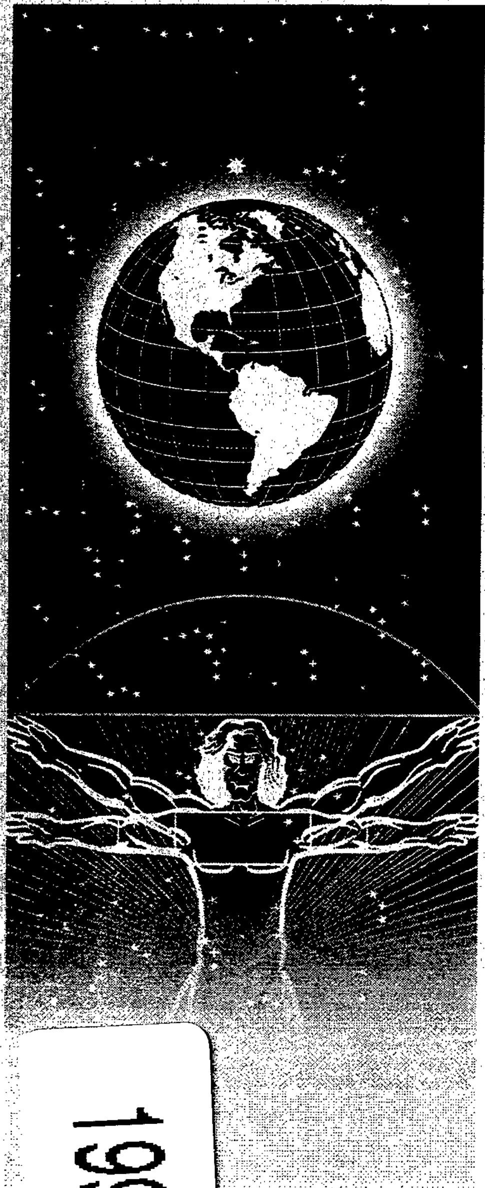

UNITED STATES AIR FORCE
ARMSTRONG LABORATORY

EFFECT OF INCOMPATIBLE LIGHT ON MODIFIED CLASS B NIGHT VISION GOGGLE-AIDED VISUAL ACUITY AND CONTRAST SENSITIVITY

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NOTICES

This report has been reviewed and is approved for publication.

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13. ABSTRACT *(Maximum 200 words)*

MIL-L-85762A, Lighting, Aircraft, Interior, Night Vision Imaging System (NVIS) Compatible, defines criteria for assessing night vision goggle (NVG) compatibility of cockpit lighting. As part of the assessment procedures, NVG-aided visual acuity (VA) is measured using the USAF Tri-Bar Chart. A cockpit light is incompatible if NVG-aided VA is degraded. An alternative method of measuring NVG-aided VA uses an NVG Chart. This research assessed whether the two NVG-aided VA assessment techniques reveal the same levels of degradation in NVG-aided VA. NVG-aided contrast sensitivity (CS) also was measured to determine its usefulness in assessing the compatibility of a cockpit light. Three NVG CS charts were developed having spatial frequencies of 3, 6, and 12 cycles per degree (cpd). NVG performance was degraded (small degradation with a green light and large degradation with a red light) by incompatible light, and the amount of degradation was assessed using the two VA and CS measures. Measurements were made using a modified Class B NVG. Another objective of this research was to assess the compatibility of the modified Class B NVG with compatible cockpit light defined in MIL-L-85762A. The results revealed that NVG-aided VA did not differ between the two VA charts. For the green light, NVG-aided CS was degraded only for the high spatial frequency (12 cpd). However, for the red light, NVG-aided CS was degraded for all three spatial frequencies. NVG-aided CS was sensitive to the presence of incompatible light. The modified Class B NVG is compatible with the lighting requirements defined in MIL-L-85762A.

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Acuity; Aircraft; Aircraft lighting; Class B filters; Cockpit lighting; Contrast Sensitivity; Filters; Lighting; Night vision goggles; Night Vision Imaging System; NVGs; NVIS; Performance measures; Visual acuity

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PREFACE

This work was conducted by the Armstrong Laboratory, Aircrew Training Research Division (AL/HRA), with support from Hughes Training, Inc. (HTI), Training Operations, located in Mesa, Arizona. The work was conducted under Work Units 1123-B4-06, Night Vision Device Training Research, and 1123-B2-06, Aircrew Training Research Support, under guidance from Dr. Elizabeth L. Martin, who is gratefully acknowledged. HTI, working under Contract F41624-95-C-5011, supports AL/HRA by supplying night vision device (NVD) subject-matter expertise in the areas of NVD research, development, and test and evaluation. This work also was in collaboration with the Department of Industrial and Management System Engineering at Arizona State University (ASU), Tempe, AZ. Support from Dr Bill Uttal at ASU is gratefully acknowledged. Also, thanks to Mr John Martin for his assistance in designing the experimental apparatus, Ms Margie McConnon for constructing the contrast charts, and Ms Marge Keslin for her superb editorial support.

This report documents the comparison of measures to assess night vision goggle (NVG) visual performance degradation due to incompatible light. Two measures assessing NVG-aided visual acuity (VA) were compared. NVG-aided contrast sensitivity (CS) also was assessed as an effective measure of compatibility. Assessments were conducted with an F4949D NVG containing a new type of minus-blue filter (modified Class B). The results of this research will aid in the re-writing of MIL-L-85762A, Lighting, Aircraft, Interior, Night Vision Imaging System (NVIS), Compatible, as a performance-based specification.

EFFECT OF INCOMPATIBLE LIGHT ON MODIFIED CLASS B NIGHT VISION GOGGLE-AIDED VISUAL ACUITY AND CONTRAST SENSITIVITY

INTRODUCTION

Night vision goggles (NVGs) greatly enhance the ability to conduct night operations and are used extensively in both rotary-wing and fixed-wing operations. NVGs provide an intensified image of scenes illuminated by ambient energy in the red and near-infrared portions of the electromagnetic spectrum (approximately 600-900 nanometers [nm]) which exist in the night environment. The luminance of the NVG image is between 2,000 and 7,000 (depending on the type of NVG used) times higher than the original scene.

NVGs employ an automatic brilliance control (ABC) feature which maintains a constant image brightness by decreasing intensifier gain in response to input light levels exceeding a defined threshold. Proximate lights emitting energy within the range of the spectral response of the NVG are considered incompatible if they activate the ABC, decreasing intensifier gain. With decreased gain, there is a corresponding decrease in image contrast which degrades NVG-aided visual performance.

Incompatible light can severely degrade NVG performance if the source is within the field of view (FOV) of the NVG. Incompatible light sources outside the FOV also can degrade NVG performance if enough light is captured and internally reflected by the glass elements of the NVG objective lens to cause veiling glare. If the veiling glare is severe, it will activate the ABC and decrease image contrast. Even if the veiling glare is not severe, some contrast loss still may occur.

The measurement of NVG-aided visual performance to assess the NVG compatibility of light is the subject of this report. In addition, a new class of NVG (modified Class B) was assessed. Two methods of measuring NVG-aided visual acuity (VA) and a measure of NVG-aided contrast sensitivity (CS) were evaluated for their effectiveness in assessing the compatibility of a cockpit light. The following sections present a description of NVG classes, an overview of the current requirements for assessing the NVG compatibility of cockpit light, and the rationale for evaluating the two NVG-aided VA and NVG-aided CS assessment techniques.

Classes of NVGs

To achieve compatibility and avoid losses in NVG-aided VA, cockpit lighting should have a spectral distribution containing little or no overlap with the spectral response of the NVG. MIL-L-85762A, Lighting, Aircraft, Interior, Night Vision Imaging System (NVIS) Compatible defines criteria for the assessment of cockpit lighting compatibility and categorizes NVGs by class. NVG-compatible cockpit lighting requirements differ depending on the class of goggle being used. NVG class categories include:

Class A: 625 nm minus-blue objective lens filter
Class B: 665 nm minus-blue objective lens filter

NOTE: MIL-L-85762A is currently being rewritten as a Performance Specification. ASC/ENFC 96-01, Lighting, Aircraft, Interior, Night Vision Imaging System (NVIS) Compatible is the current document governing the NVG compatibility for the Air Force. The requirements define NVG compatibility of cockpit lighting in ASC/ENFC as nearly identical to MIL-L-85762A. For purposes of this report, the two can be used interchangeably.

Class A and Class B NVGs differ in the spectral transmission characteristics of their minus-blue objective lens filter. In general terms, Class A NVGs are filtered so they will not sense and intensify light at wavelengths shorter than the orange region of the spectrum (50% transmission at 625 nm), and Class B NVGs are filtered so they will not sense and intensify light at wavelengths shorter than the middle red region of the spectrum (50% transmission at 665 nm). Class B filters allow the use of multicolored displays and red warning or caution indicators. The relative spectral response of Class A and Class B NVGs is presented in Figure 1.

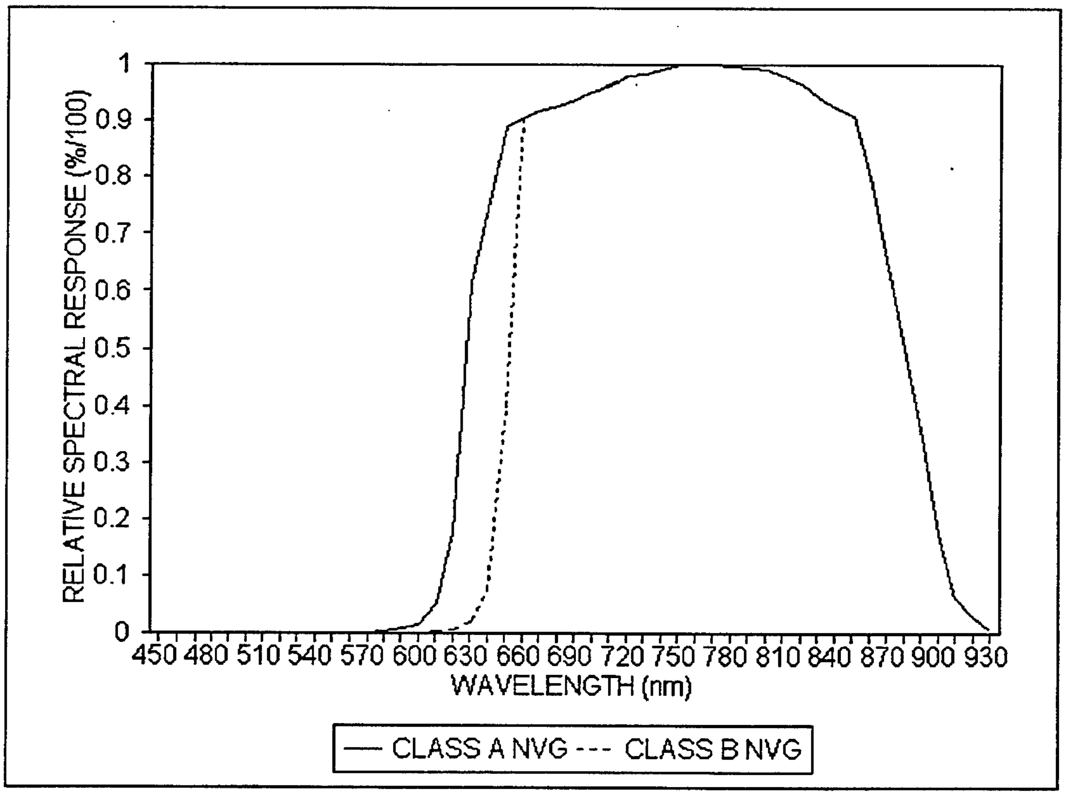

Figure 1
Relative Spectral Response of Class A and Class B NVGs

Aircraft head-up display (HUD) information is viewed directly with the NVG. Therefore, a portion of the spectral output of the HUD must be within the response range of the NVG. The NVG then will intensify the HUD imagery, reproducing it in the goggle image. The source of HUD emission is a cathode ray tube (CRT) with either a P1, P43, or P53 phosphor (green colored). Emissions from these phosphors share a common trait. Substantial energy is emitted at 545 nm, and little energy is emitted at other wavelengths. When viewing HUDs, a Class A NVG filter, with its wider spectral transmission, will pass enough HUD energy to allow intensification of HUD symbology. A Class B NVG filter ordinarily does not transmit enough energy from the HUD to allow intensification of HUD information.

To date, the filters in NVGs fielded for use by the Air Force have not transmitted enough energy from the HUD to consistently provide adequate readability of HUD imagery. In some aircraft, aviators have been forced to increase HUD brightness to view the HUD through NVGs. The HUD holographic combiner in F-16C Block 40/42 aircraft ordinarily will not allow HUD emissions to be visible to currently fielded NVGs. Recently, a new type of filter has been developed which preserves current NVG imaging capabilities while also permitting viewing of HUD imagery in the intensified image.

A prototype filter, developed by ITT Defense & Electronics, Electro-Optical Products Division, modifies the characteristics of a Class B filter with an added bandpass feature to allow limited transmission of energy in the region of peak emission of HUDs (approximately 545 nm). The filter is intended to allow readability of the HUD without degrading compatibility with either Class A or Class B cockpit lighting. The design of the modified Class B filter was based on the calculated theoretical response of an F4949D NVG (the most technically advanced NVG fielded at the time) to representative HUD phosphor emissions. Calculations supporting the design predicted that a filter having 1% transmission at 545 nm, when fitted to an F4949D NVG, would provide a sufficient intensification of HUD emission. Figure 2 presents the relative spectral response of the modified Class B filter on an F4949D NVG.

The spectral energy distribution of NVG-compatible cockpit lighting generally peaks between 530 and 560 nm, coinciding with the bandpass of the modified Class B filter. This raised concerns as to whether the modified filter might permit sufficient intensification of "compatible" green cockpit light to affect NVG gain and degrade NVG-aided VA, or whether the filter might transmit excessive HUD energy and cause a similar effect. However, a recent evaluation by Reising, Martin, and Berkley (1996) revealed that the modified Class B filter did not degrade NVG-aided VA in NVG-compatible aircraft currently fielded in the Air Force. A laboratory assessment has not been conducted to determine whether the modified Class B filter is compatible with the specific requirements defined in MIL-L-85762A. This research is required because MIL-L-85762A is currently in the process of being rewritten and updated. The question exists as to whether the requirements defined in MIL-L-85762A need to be modified to address the modified Class B NVG. Thus, an objective of the present research was to determine whether the Class B filter is compatible with the current requirements defined in MIL-L-85762A.

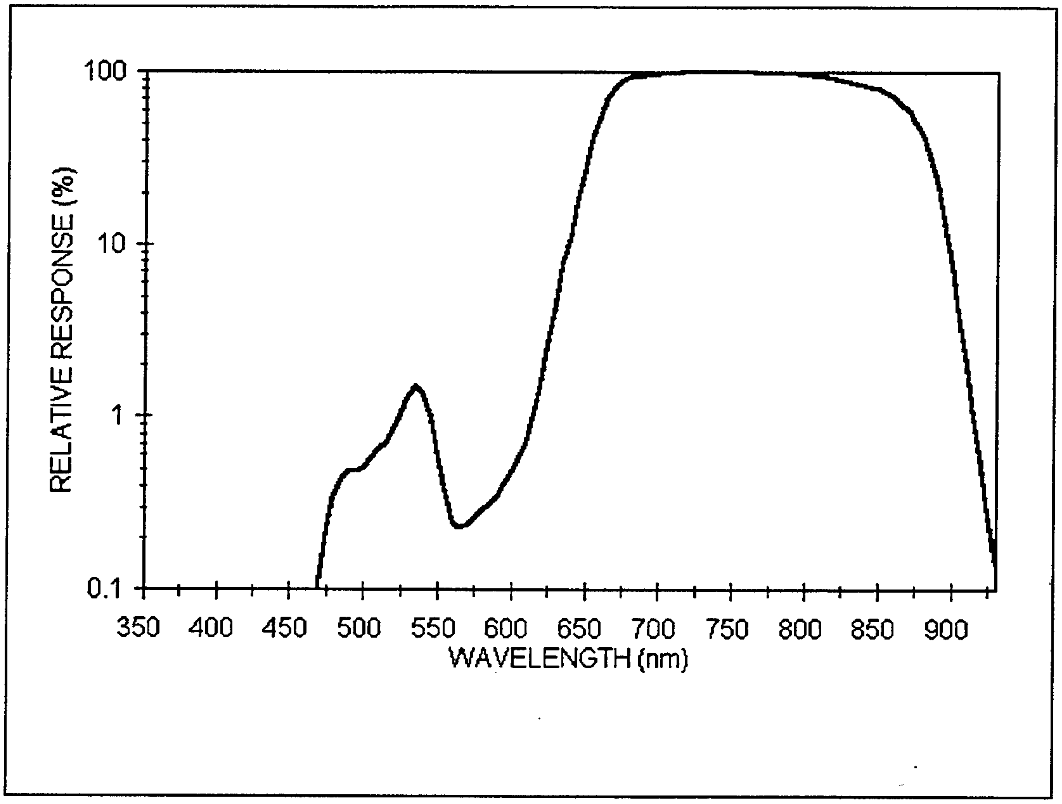

Figure 2
Relative Spectral Response of a Modified Class B F4949D NVG (as measured in the laboratory)

Assessing the NVG Compatibility of Cockpit Light

MIL-L-85762A requires that NVG-aided VA be measured to determine whether the cockpit lighting degrades NVG performance. MIL-L-85762A states that a USAF 1951 Medium Contrast Resolution Resolving Power Target (USAF Tri-Bar Chart) be used for the assessment. The cockpit lighting is compatible if no degradation in NVG-aided VA is observed by the subject.

MIL-L-85762A specifies that NVIS radiance (NR) be measured from the illuminated USAF Tri-Bar Chart. NR is the amount of energy from a source that is sensed by the NVG (integral, from 450 to 930 nm, of the product of NVG relative spectral response x spectral radiance of energy source). The illumination on the chart is adjusted so that the NR from the white portion of the chart is equivalent to the amount of energy within the spectral response of the NVG that would be reflected from a defoliated tree under starlight conditions, the standard referent on which the specification was based.

There is very little energy available for the NVG to render an image, and the result is a noisy (i.e., highly scintillated) and poorly detailed image. Therefore, if cockpit lighting degrades acuity to a level where trees under starlight conditions cannot be resolved, then the lighting is incompatible with NVGs (Reetz, 1987).

The requirements defined in MIL-L-85762A for maximum allowable energy (i.e., NR) of cockpit lights are based upon research conducted by Bryner (1986). She placed various colored lights (mainly shades of orange-red) within the FOV of the NVG and varied the intensity of the lights. Subjects were required to view the USAF Tri-Bar Chart (high contrast) and determine whether NVG-aided VA was degraded by the light. She measured NR for both Class A (NR_A) and Class B (NR_B) NVGs. The results revealed that average NVG-aided VA degraded by 8.6% with an NR_B of 1.40×10^{-7}. A degradation of 8.6% was considered acceptable, and 1.40×10^{-7} was chosen as the maximum allowable NR_B for cockpit lights. The same colored light produced an NR_A of 3.30×10^{-7} and degraded Class A NVG-aided VA by 14%. This amount of degradation was considered excessive and, therefore, cockpits in which Class A NVGs are used are restricted from containing red light.

<u>NVG-Aided Visual Acuity</u>. The USAF Tri-Bar Chart contains a standard pattern of three vertical bars (square-wave grating patterns) adjacent to three horizontal bars along with an identifying number (see Fig. 3). The pattern is repeated throughout the chart for various spatial frequencies. The spatial frequencies vary in 0.05 log unit steps (approximately 11%). The contrast (measured as contrast modulation [$Luminance_{max}$ - $Luminance_{min}$]/[$Luminance_{max}$ + $Luminance_{min}$]) is 0.70. The procedure requires a subject to focus NVGs on the USAF Tri-Bar Chart to obtain maximum resolution (highest spatial frequency in which three vertical and three horizontal bars are distinguishable). Cockpit lighting is illuminated while the subject views the chart and assesses whether resolution is degraded.

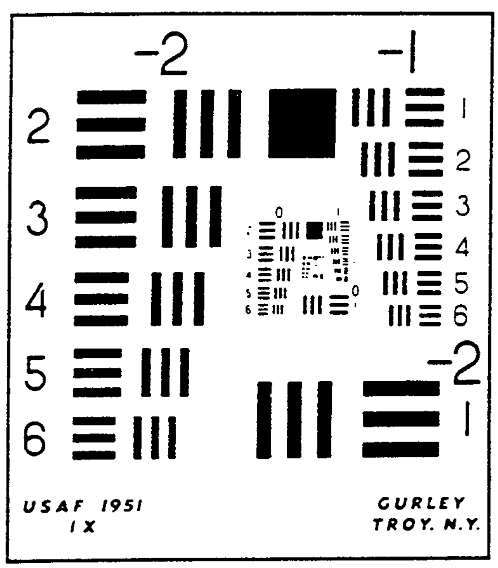

Figure 3
Representation of the USAF Tri-Bar Chart

The format of the USAF Tri-Bar Chart may result in a decision bias that can affect the determination of compatibility. Because the standard three-bar pattern is repeated throughout the chart, the solution to the pattern is always known to the observer. Furthermore, the procedure requires a highly subjective determination of whether or not a pattern can be resolved. As a result of the subjective nature of the measure, high variability (both between- and within-subjects) may exist, and repeatable results may be difficult to obtain. It is difficult for subjects to consistently determine their threshold of resolution because the energy reflected from the chart is low, resulting in scintillation in the NVG image. Scintillation causes the perception that the resolution of high spatial frequencies "fades in and out." This degraded image, combined with the subjects' knowledge of the chart's pattern, may cause inconsistencies in reported resolution.

To overcome the possible problem of decision bias associated with NVG-aided VA measurements with the USAF Tri-Bar Chart, the Air Force Armstrong Laboratory designed a new resolution chart to be used for cockpit lighting evaluations (Reising, Antonio, & Fields, 1996). The NVG Chart (see Fig. 4) contains 16 square-wave grating patterns (eight vertical and eight horizontal), randomly configured on the chart, which represent Snellen acuities of 20/20 to 20/70 (the 20/35 through 20/55 patterns are presented twice). The chart is resolved at a viewing distance of 6.1 m (20 ft). The step size between spatial frequencies continually decreases from high to low spatial frequencies. For example, from 15.1 to 13.2 cycles per degree (cpd) (20/40 to 20/45 equivalent Snellen acuity), the size of the square-wave gratings changes by 11%. However, from 8.0 to 7.5 cpd (20/75 to 20/80 equivalent Snellen acuity), the size of the grating changes by 6%. The contrast modulation of the chart is 0.50. For conditions in which NVG-aided VA degradation is severe, a second chart has been developed containing square-wave gratings representing Snellen acuities of 20/50 to 20/90 (patterns representing 20/60 to 20/90 are repeated on the low spatial frequency chart). Table 1 indicates the spatial frequencies presented on the charts. The procedure requires a subject to "read" the NVG Chart resolution patterns from left to right and top to bottom. The chart is rotated 90 degrees when every pattern is "read." Thus, each pattern is viewed four times. The subjects indicate whether a pattern is vertical, horizontal, or cannot be resolved. The number of correct vertical and horizontal responses is totaled and ranked from high to low spatial frequency. VA is determined as the highest spatial frequency correctly identified 75% of the time. For example, if a subject correctly identifies the 20/55 pattern 100% of the time (8 of 8), the 20/50 pattern 75% of the time (6 of 8) and the 20/45 pattern 62.5% of the time (5 of 8), the subject's VA is assessed as 20/50.

Discrepancies in results between the USAF Tri-Bar Chart and the NVG Chart have occurred during cockpit lighting evaluations. An evaluation of a C-130H3 aircraft revealed that reported degradation of NVG-aided VA differed by 24% between subjects (Reising, Grable, Stearns, Craig, & Pinkus, 1995). Both the USAF Tri-Bar Chart and the NVG Chart were used in this evaluation. During one of the assessments, NVG-aided VA measured from a subject with the NVG Chart identified degradation that was not reported by the same subject when viewing the USAF Tri-Bar Chart. It is unknown whether this was due to the difference in contrast between the two charts, differences in the step size from one spatial frequency to another between the two charts, or that the NVG-aided VA obtained with the USAF Tri-Bar Chart is more susceptible to decision bias than that obtained with the NVG Chart.

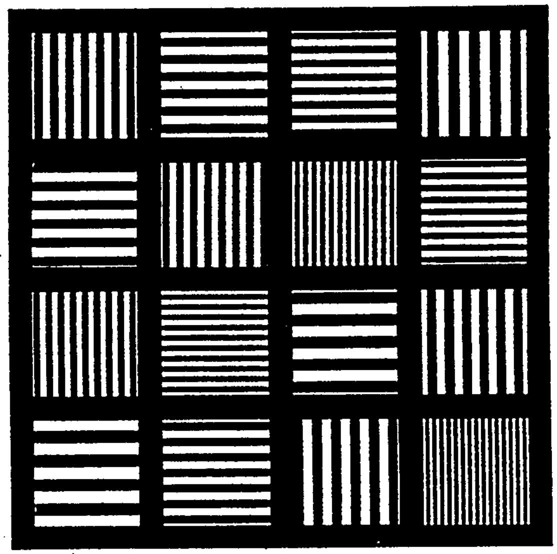

Figure 4
Representation of the NVG Chart

Table 1. Spatial Frequency in Cycles Per Degree (Equivalent Snellen Acuity) of Patterns on NVG Charts

High Range	Low Range
30.0 (20/20)	12.0 (20/50)
24.0 (20/25)	10.5 (20/55)
19.8 (20/30)	10.0 (20/60)
17.0 (20/35)	10.0 (20/60)
17.0 (20/35)	9.2 (20/65)
15.1 (20/40)	9.2 (20/65)
15.1 (20/40)	8.5 (20/70)
13.2 (20/45)	8.5 (20/70)
13.2 (20/45)	8.0 (20/75)
12.0 (20/50)	8.0 (20/75)
12.0 (20/50)	7.5 (20/80)
10.5 (20/55)	7.5 (20/80)
10.5 (20/55)	7.1 (20/85)
10.0 (20/60)	7.1 (20/85)
9.2 (20/65)	6.7 (20/90)
8.5 (20/70)	6.7 (20/90)

An objective of the present research was to compare the USAF Tri-Bar Chart and NVG Chart to determine whether NVG-aided VA results differ when incompatible light of a known intensity is present. This information is useful because time is limited during most cockpit lighting evaluations, and highly accurate results are necessary. The USAF Tri-Bar Chart is logistically preferred over the NVG Chart for cockpit lighting evaluations because it is easier to use, requires less time to record a measurement, and is not as dependent upon the distance between the chart and the viewer.

NVG-Aided Contrast Sensitivity. Most real-world tasks require the resolution of many spatial frequencies under primarily medium and low contrast conditions. VA measurements address spatial resolution at one contrast level (70% for the USAF Tri-Bar Chart and 50% for the NVG Chart). CS measures the contrast threshold for a particular spatial frequency and allows the researcher to choose which spatial frequencies to measure (representing different stimulus sizes). The CS information combined with VA may provide a more comprehensive index of visual performance than simply VA alone. The measurement of CS has been investigated to determine whether it is better related to real-world task performance than VA, and the results have been inconclusive (Ginsburg, Easterly, & Evans, 1983; Ginsburg, Evans, Sekule, & Harp, 1982; Kruk & Regan, 1983; Kruk, Regan, Beverley, & Longridge, 1981; 1983; O'Neal & Miller, 1988).

Rabin (1995) determined that CS of small letters (20/25 Snellen equivalent) was better than VA at predicting performance under degraded conditions (i.e., defocused image under low luminance) similar to those encountered when wearing NVGs. Rabin (1993) also measured NVG-aided CS under varying illumination levels. He found that as illumination levels decreased, CS for high spatial frequencies was affected more than lower spatial frequencies.

Objective measurements have revealed that incompatible light causes a loss of contrast in the NVG image (Reising, Martin, & Gregory, in process). Therefore, NVG-aided CS provides a direct visual performance measure of the presence and magnitude of incompatible light. It is unknown whether incompatible cockpit light may affect the contrast threshold for some spatial frequencies differently than other spatial frequencies. Therefore, another objective of this research was to validate NVG-aided CS as an alternative measure of the presence of incompatible light.

The Present Experiment

There were three objectives of this experiment. One objective was to compare NVG-aided VA data obtained with both the NVG Chart and the USAF Tri-Bar Chart. A second objective was to determine whether NVG-aided CS is sensitive to the negative effects caused by the presence of an incompatible light. Contrast threshold data were compared between three different spatial frequencies to determine whether cockpit light degrades sensitivity equally at different spatial frequencies. A third objective was to determine whether NVG-compatible green light (as defined in MIL-L-85762A) degrades NVG-aided visual performance with the modified Class B filter. If NVG-aided VA is not degraded, then the Modified Class B filter is compatible with the current requirements defined in MIL-L-85762A for Class B NVGs. To achieve the objectives, an experimental configuration similar to the one used by Bryner (1986) was incorporated. Lighting components were placed in the FOV of the NVG. Visual performance measurements were obtained under conditions of no incompatible light and incompatible lights of varying intensity.

METHOD

Subjects

Twenty subjects (18 male, 2 female) volunteered for the experiment. All subjects had at least 20/22 photopic VA as measured with the USAF Tri-Bar Chart. Subjects also received specific training on F4949 NVG adjustment procedures (Antonio & Berkley, 1993). Ages ranged from 22 to 51 years with a mean of 31.1 years. Four of the subjects had extensive flight experience with NVGs, and two currently are NVG instructor pilots. All subjects demonstrated at least 20/35 NVG-aided VA after NVG adjustment.

Apparatus and Stimuli

NVG-aided VA was measured using the USAF Tri-Bar and NVG Charts described in the Introduction section. NVG-aided CS was measured using charts designed for this research. NVG-aided CS was assessed at three spatial frequencies: 12, 6, and 3 cpd. These spatial frequencies are approximately equivalent to Snellen acuities of 20/50, 20/100, and 20/200, respectively, and are identical to those examined in previous NVG-aided CS research (Rabin and McLean, 1996). The spatial frequencies consisted of square-wave gratings and were placed in a 4 x 4 configuration on the charts similar to the NVG Chart previously described. It was not practical to develop sine-wave grating charts (used in many CS assessments) for this research. However, as pointed out by Shapely and Lam (1993), there is little or no evidence to show that CS measurements during clinical assessments made with sine-wave gratings provide different results than those made with square-wave gratings. The contrast patterns were generated using computer graphics software and printed via a laser printer. The contrast of each target was measured with a Photo Research PR-1980A Photometer. The contrast levels of the gratings varied in approximately 0.05 log unit steps (due to variations in the saturation of computer printer ink, precise unit steps could not be obtained). Table 2 presents the contrast (modulation) of targets placed on each chart.

All charts were placed 6.1 m (20 ft) from the objective lens of the NVG. The charts were illuminated by a Hoffman LS-65-GS Integrating Sphere. Radiance from the white portion of the charts was adjusted to the criterion defined in MIL-L-85762A (1.60 x 10^{-10} NR_B). The radiance was measured with a Photo Research PR-1530AR NVISpot Meter. The NVG used was an ITT F4949D (S/N 2590) fitted with modified Class B objective lenses and mounted on a chin rest.

Table 2. Contrast (%) of Gratings on NVG-Aided CS Charts

SPATIAL FREQUENCY CHART		
12 cpd	6 cpd	3 cpd
88.8	44.0	24.8
80.7	39.0	21.6
69.1	31.8	18.1
63.7	28	15.3
55.2	25	13.8
49.5	21	12.3
44.4	17.9	11.6
42.3	16.2	9.9
35.3	14.3	9.1
31.5	12	8.0
28.2	11.6	7.3
26.1	10.8	6.6
22.9	8.5	4.7
18.3	7.6	4.1
17.4	6.7	3.9
16.8	4.1	3.0

A 20-watt/24-volt tungsten halogen bulb was enclosed in a metal housing and powered by a DC power supply. The light was placed 50.8 cm (20 in) directly in front of the objective lens of the NVG and positioned to emit energy at approximately a 10-deg angle. This configuration simulated the location of a warning indicator in most fighter aircraft. When a subject viewed the charts with the NVG, the light source was in the lower center of the NVG FOV, and the NVG FOV appeared to be evenly affected by the incompatible light. Foveal vision was not obstructed by the physical elements of the light and metal housing. Figure 5 presents a representation of the experimental configuration.

One of two filters was placed in front of the light. For both filter/light configurations, the area emitting energy was approximately 2.54 cm^2 (1 in^2). An NVIS Green B filter (NV-2GB) made by Wamco, Inc. was used to provide a minimal degradation condition. (Various NVIS Green A and Green B filters were sampled from a number of filter manufacturers. The NV-2GB filter was chosen because it provided the highest spectral transmission at 545 nm of all NVIS filters evaluated, and thus would be the least compatible with the bandpass of the modified Class B NVG.) A Wamco, Inc. NVIS red filter (NV-6RC-10) was chosen to provide a large degradation condition. Although designed to be compatible with most cockpit light sources, the NVIS red filter is incompatible with NVGs under high radiance conditions (Bryner, 1986). The spectral transmission of the filters and the response of the modified Class B NVG are presented in Figure 6. As illustrated, the NVIS Green B filter transmission peaks at 545 nm, as does the bandpass of the modified Class B feature. The transmission of the NVIS red filter overlaps with the response of the NVG, and this overlap is a potential cause of incompatibility.

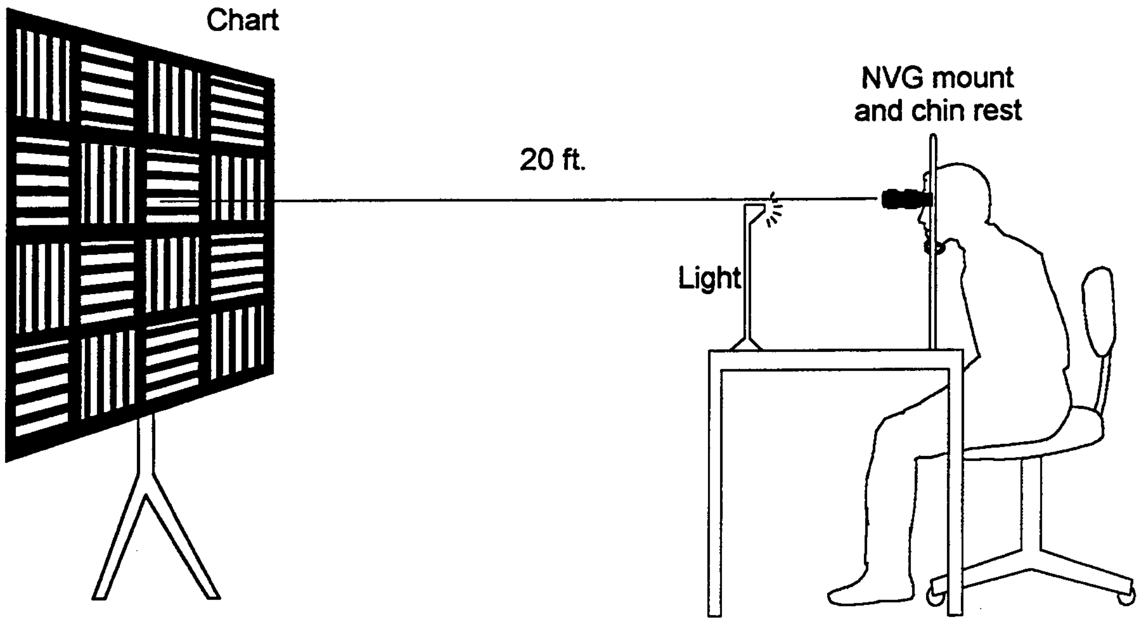

Figure 5
Representation of the Experimental Configuration

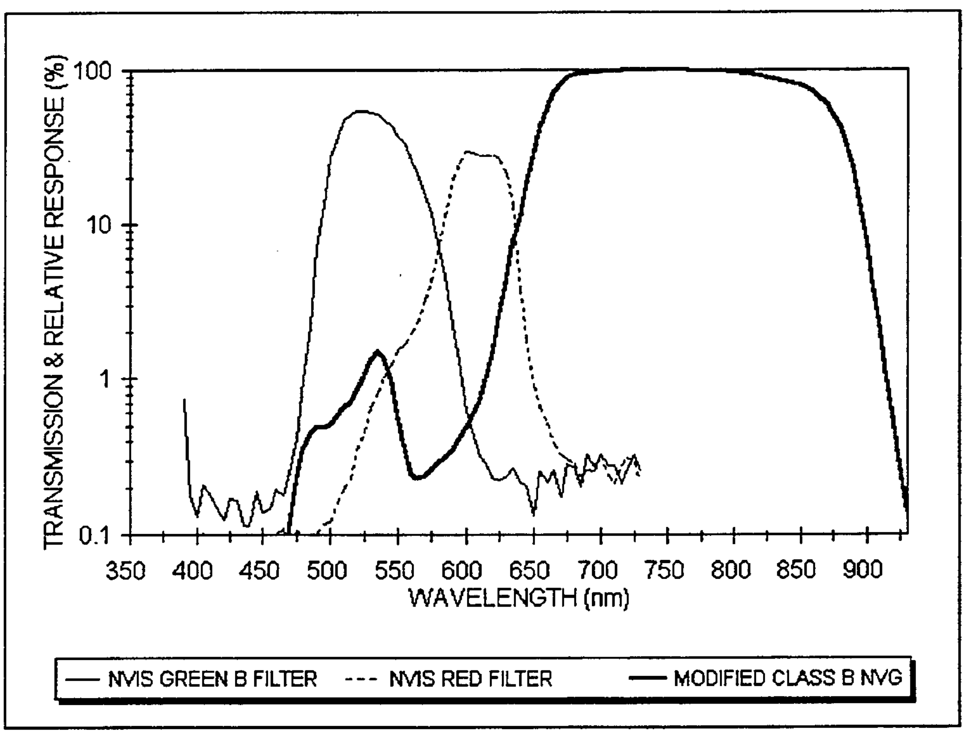

Figure 6
Spectral Transmission of NVIS Green B and NVIS Red Filters and
Relative Response of the Modified Class B NVG

Data were collected from two subjects to determine the level of radiance for the light/filter configurations used in the present experiment. The small degradation condition (green light) was determined by the following procedure: The Green B light was illuminated to produce 1.40×10^{-7} NR_B (maximum allowed NR in MIL-L-85762A). NVG-aided VA was measured with the USAF Tri-Bar Chart, and no degradation was observed. The voltage of the light was then increased until a slight degradation on the USAF Tri-Bar Chart was observed (one element loss of approximately 11%). The radiance at this level was then measured from a Hoffman Engineering SRS-2 Spectral Reflectance Standard using a Photo Research PR-1530AR NVISpot Meter, and calculated using the inverse square law. Luminance was measured from the filter/light configuration using a Minolta LS-110 photometer. The large degradation condition (red light) was determined with the same procedures. However, radiance was increased until at least a two- to three-element loss (22 to 33% degradation) was observed on the USAF Tri-Bar Chart. Radiance and luminance data are presented in Table 3.

Table 3. Radiance and Luminance of the Filter/Light Configurations

	NVIS GREEN B	NVIS RED
NVIS RADIANCE (NR_B)	4.00×10^{-7}	2.20×10^{-6}
LUMINANCE	259.0 (fL)	200.0 (fL)
	887.3 (cd/m^2)	685.2 (cd/m^2)

Procedure

The procedure for determining NVG-aided VA using the NVG Chart and determining NVG-aided CS is taken from DeVilbiss and Antonio (1994). As mentioned in the Introduction section, each subject "read" the resolution patterns from left to right and top to bottom under each of the four possible chart orientations. The number of correct responses was totaled, and VA (or contrast threshold) was determined as the highest spatial frequency (or lowest contrast) correctly identified 75% of the time. If a subject could not resolve any patterns, contrast threshold was assigned a value of 100. For the determination of NVG-aided VA with the USAF Tri-Bar Chart, subjects were instructed to identify the highest spatial frequency in which three horizontal and three vertical bars (with two white spaces in-between) were clearly visible.

Experimental Design

For comparison of the NVG-aided VA charts, the experiment employed a 2 x 3 within-subjects factorial design. The independent variables consisted of VA CHART (NVG Chart, USAF Tri-Bar Chart) and LIGHT (No Light, NVIS Green B Light, and NVIS Red Light). The dependent variable consisted of NVG-aided VA (reported as Snellen acuity).

For the assessment of NVG-aided CS, the experiment employed a 3 x 3 within-subjects factorial design. The independent variables consisted of CS SPATIAL FREQUENCY (3, 6, and 12 cpd), and LIGHT (No Light, NVIS Green B Light, and NVIS Red Light). The dependent variable consisted of NVG-aided CS threshold. CS is typically expressed as the reciprocal of contrast threshold. However, to ease interpretation and discussion of the results, only threshold data are presented. Each subject participated in 15 measurement conditions (2 VA CHARTS x 3 LIGHTS and 3 CS SPATIAL FREQUENCY x 3 LIGHTS). The order of the conditions was randomized across subjects. All statistical analyses were conducted with SPSS for Windows, Release 6.3.1.

RESULTS

NVG-Aided Visual Acuity

A 2 x 3 within-subjects analysis of variance (ANOVA) was conducted on the NVG-aided VA data (20/XX). The results of the ANOVA revealed a main effect of LIGHT ($F[2,38] = 87.52$, $p < 0.001$). The main effects of VA CHART and the interaction of VA CHART x LIGHT were not significant. Because it was known a priori that the main effect of LIGHT would be significant (NR levels were adjusted until two subjects identified degradation), no further analyses were conducted. The ANOVA summary is presented in Table 4; means and standard deviations are presented in Table 5.

Table 4. NVG-Aided Visual Acuity ANOVA Summary Table

Source	Degrees of freedom	Sum of squares	F-value	p
VA CHART	1	0.05	0.00	= 0.971
LIGHT	2	5594.43	87.52	< 0.001
VA CHART x LIGHT	2	4.85	0.11	= 0.894
VA CHART x SUBJ	19	728.78		
LIGHT x SUBJ	38	1214.51		
VA CHART x LIGHT x SUBJ	38	821.43		

To assess whether one chart produced more variable results than another, a Hartley's F_{max} test for homogeneity of variance was conducted on the CHART data at each LIGHT condition. This analysis compares the ratio of the largest to smallest variance of the conditions with the F sampling distribution. The results revealed that at the No light condition, F_{max} was 1.12; at the NVIS Green B light condition, F_{max} was 1.79; and at the NVIS Red light condition, F_{max} was 1.74. The F_{crit} was 2.54; thus, the variance between the two charts was not significantly different across the three LIGHT conditions ($p > 0.05$).

Table 5. Mean and Standard Deviation NVG-Aided Visual Acuity

LIGHT	No Light	
VA CHART	NVG Chart	USAF Tri-Bar Chart
MEAN	49.00	48.50
SD	4.47	4.23
LIGHT	NVIS Green B Light	
VA CHART	NVG Chart	USAF Tri-Bar Chart
MEAN	55.00	55.45
SD	4.29	5.74
LIGHT	NVIS Red Light	
VA CHART	NVG Chart	USAF Tri-Bar Chart
MEAN	65.25	65.43
SD	11.30	8.56

NVG-Aided Contrast Sensitivity

A 3 x 3 within-subjects ANOVA was conducted on the NVG-aided contrast threshold data. The results of the ANOVA revealed main effects of CS SPATIAL FREQUENCY ($F[2,38] = 213.57$, $p < 0.001$) and LIGHT ($F[2,38] = 64.00$, $p < 0.001$). The interaction also was significant: CS SPATIAL FREQUENCY x LIGHT ($F[4,76] = 46.86$, $p < 0.001$). The ANOVA summary is presented in Table 6; means and standard deviations are presented in Table 7.

An analysis of simple effects was conducted on the two-way interaction to examine the effect of LIGHT at each SPATIAL FREQUENCY. The analysis revealed that LIGHT was significant at each SPATIAL FREQUENCY. The simple effects analysis summary is presented in Table 8.

A Tukey's HSD test was conducted on the NVG-aided contrast threshold LIGHT means at each SPATIAL FREQUENCY to identify the locus of the LIGHT effect. The results revealed that mean NVG-aided CS, when viewing the 12 cpd chart with the NVIS Red Light, was significantly worse than CS with the NVIS Green Light, which also was significantly worse than CS with No Light. Mean NVG-aided CS when viewing both the 3 and 6 cpd charts with the NVIS Red Light was significantly worse than CS with both the NVIS Green and No Light conditions (NVIS Green and No Light CS did not significantly differ). The means are displayed in Figure 7 for NVG-aided contrast threshold data.

Table 6. NVG-Aided Contrast Threshold ANOVA Summary Table

Source	Degrees of freedom	Sum of squares	F-value	p
SPATIAL FREQ.	2	105744.26	213.57	< 0.001
LIGHT	2	11728.42	64.00	< 0.001
SPATIAL FREQ. x LIGHT	4	15517.10	46.86	< 0.001
SPATIAL FREQ. x SUBJ	38	9407.46		
LIGHT x SUBJ	38	3481.62		
SPATIAL FREQ. x LIGHT x SUBJ	76	6291.43		

Table 7. Mean and Standard Deviation NVG-Aided Contrast Threshold

LIGHT	No Light		
SPATIAL FREQ.	12 cpd	6 cpd	3 cpd
MEAN	35.69	9.48	7.00
SD	10.52	2.94	1.97
LIGHT	NVIS Green B Light		
SPATIAL FREQ.	12 cpd	6 cpd	3 cpd
MEAN	59.70	11.13	6.66
SD	29.87	5.31	2.27
LIGHT	NVIS Red Light		
SPATIAL FREQ.	12 cpd	6 cpd	3 cpd
MEAN	87.48	14.96	8.84
SD	19.66	7.04	3.47

Table 8. NVG-Aided Contrast Threshold Simple Effects Analysis Summary Table

Source	Degrees of freedom	Sum of squares	F-value	p
LIGHT @ 20/50.	2	26874.72	54.76	< 0.001
LIGHT @ 20/100	2	315.67	17.11	< 0.001
LIGHT @ 20/200	2	55.12	10.78	< 0.001
LIGHT x SUBJ @ 20/50	38	9325.32		
LIGHT x SUBJ @ 20/100	38	350.54		
LIGHT x SUBJ @ 20/200	38	97.19		

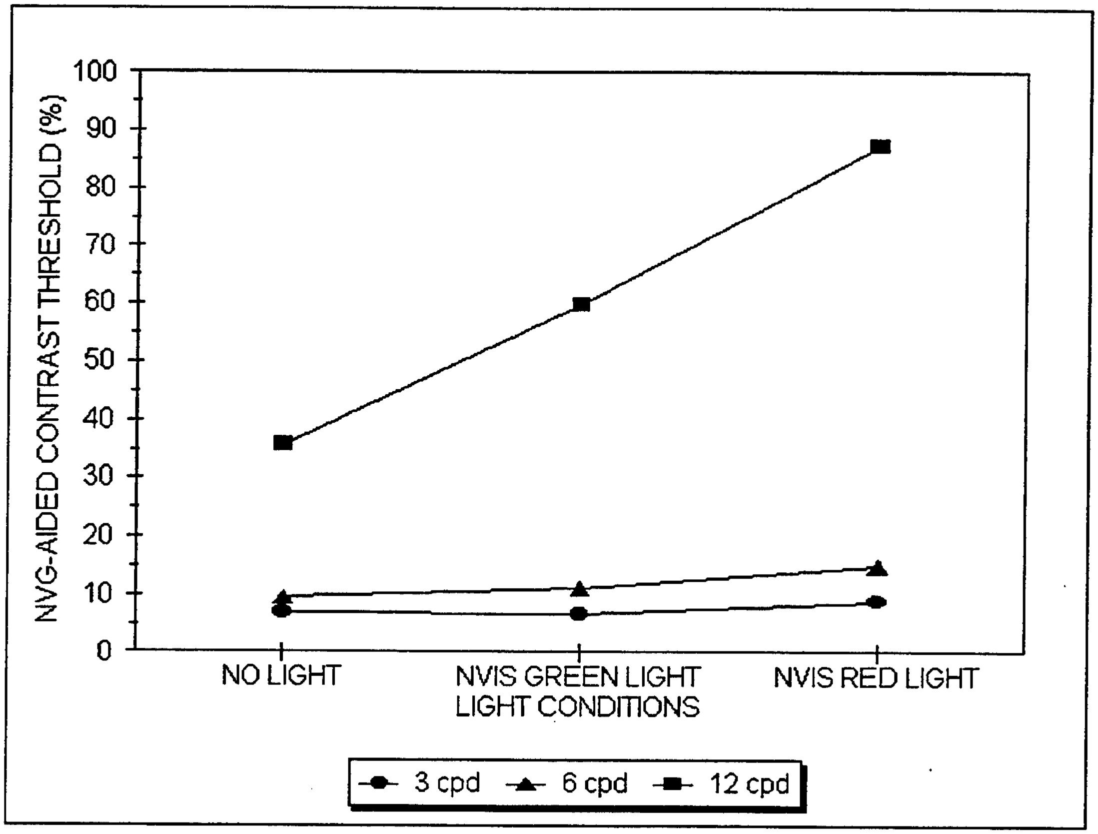

Figure 7
NVG-Aided Contrast Threshold as Function of Spatial Frequency and LIGHT

Green Light and the Modified Class B NVG

A third objective of this research was to determine whether the Modified Class B filter is compatible with the current requirements defined in MIL-L-85762A. Because the filter is Class B with an added feature (i.e., 1% transmission at 545 nm), the only possible concern is that the filter might excessively transmit MIL-L-85762A compatible green light, causing degradation of NVG performance. As mentioned previously, the data obtained for determining the radiance of the light conditions were collected from two subjects. Initially, the radiance of the light was adjusted to 1.40 x 10^{-7} NR_B (the maximum allowable radiance specified in MIL-L-85762A). At this level, no degradation of NVG-aided VA was observed by either subject. After increasing the radiance, degradation was not observed until the radiance reached 4.00 x 10^{-7} NR_B, approximately three times higher than the maximum allowed radiance. Furthermore, to obtain this higher radiance, the luminance was 259 fL, approximately 17 times higher than the maximum specified luminance (15 fL for a warning indicator). Because degradation did not occur until the radiance was much higher than that allowed by MIL-L-85762A, it was concluded that NVIS Green B light does not negatively affect NVG performance with a modified Class B filter.

DISCUSSION

Mean NVG-aided VA and subject variability in NVG-aided VA did not significantly differ between the USAF Tri-Bar Chart and the NVG Chart. It was thought that a decision bias with the USAF Tri-Bar Chart might reveal different results from those obtained with the NVG Chart. An examination of individual subject data revealed that three subjects did not report a degradation of VA with the USAF Tri-Bar Chart when the green light was illuminated. However, with the NVG Chart, a degradation of VA was measured from two of the same three subjects with the green light illuminated. This examination of the individual data highlights the problem of subject variability that can occur when using small sample sizes. This experiment used a sample size of 20 subjects, and most cockpit lighting evaluations use a sample size of two or three. Because the two charts did not statistically differ, it is recommended that the USAF Tri-Bar Chart continue to be the primary method of measuring NVG-aided VA during cockpit lighting evaluations. The reason for this recommendation is because measurement with the USAF Tri-Bar Chart requires less time and is logistically easier to use. However, at least two subjects should be used for the assessment to ensure that differences in decision criterion for identifying the resolution threshold do not affect the results. Furthermore, because the possibility exists that one subject's decision criterion may differ from that of another subject, the NVG Chart should be used as a final determinant when two subjects report different levels of resolution degradation.

Reetz (1987) discusses the rationale behind the requirements defined in MIL-L-85762A. A medium-contrast USAF Tri-Bar Chart is described, but the reason for choosing medium contrast is not mentioned. The USAF Tri-Bar Chart is designed with three different contrast modulations: high (0.99), medium (0.70), and low (0.19). However, the 70% contrast chart used to assess NVG-compatible cockpit lighting is not representative of most real-world scenes imaged by NVGs. Howard and Burnidge (1994) examined the spectral reflectivity of 105 natural and man-made objects. They computed values to represent the sensitivity of NVGs to the energy reflected from these objects. Using these NVG sensitivity values, one can compute scene contrast modulation by pairing one object next to another (e.g., green grass next to asphalt). Assessing all pair-wise comparisons of 105 objects reveals that 45% of real-world scene contrast modulation (as sensed by NVGs) is between 0.01 and 0.20, 34% is between 0.21 and 0.40, 18% is between 0.41 and 0.60, and only 3% is between 0.61 and 0.80 (none of the object pairs assessed produced contrast modulation between 0.81 and 1). These data underscore the point that 0.70 contrast modulation is not representative of the majority of scenes sensed by NVGs. Furthermore, the 0.50 contrast modulation of the NVG Chart also is not representative of the majority of scenes sensed by NVGs. It may be that a lower contrast resolution target (e.g., 0.19) provides meaningful information regarding degradation due to incompatible light. In addition, a lower contrast resolution target may be more sensitive to negative effects associated with incompatible light than the 0.50 or 0.70 contrast resolution targets. Future research should address the contrast levels of visual performance measures in the laboratory compared to those actually encountered in the real world.

NVG-aided CS was sensitive to the presence of an incompatible light, but the effect was not the same for each spatial frequency. Both the red and green light conditions significantly affected the subjects' contrast thresholds while viewing the 12 cpd chart. However, only the red light significantly affected the subject's contrast thresholds while viewing both the 6 and 3 cpd charts. Thus, resolution of high spatial frequencies is affected by both low and high levels of incompatible light. However, resolution of lower spatial frequencies is affected only by high levels of incompatible light.

The methodology used in this research does not provide a direct comparison of VA and CS. However, it is interesting to note the relative change among the measures under the same experimental conditions. The percentage change in NVG-aided VA from baseline (no light) was approximately 12% in the green light condition, which corresponds to a percentage change in NVG-aided CS of 40% at 12 cpd, 15% at 6 cpd, and 0% at 3 cpd. These data demonstrate that CS can be used to compliment VA in assessing whether NVG-aided visual performance is degraded. Although absolute percent change was higher for NVG-aided CS than NVG-aided VA, it cannot be interpreted that CS was more sensitive to the presence of an incompatible light than VA. A slight change in methodology can allow for this determination. If both CS and VA assessments are taken at small incremental changes in the intensity of an incompatible light, a specific breaking point may be identified where one measure reveals a degradation in visual performance, and the other measure fails to reveal degradation.

The design of the three CS charts provided an adequate measure of NVG-aided CS. The selected ranges of contrast levels for each spatial frequency, from the lowest to the highest, were sufficient for all subjects at the baseline and green light conditions. However, in the red light condition, NVG-aided CS was severely degraded, and 13 of 20 subjects could not resolve any patterns on the 12 cpd chart. An accurate measurement could not be obtained, and the contrast required for resolution was greater than 88.8% (the maximum contrast target on the 12 cpd chart). A slightly lower spatial frequency (e.g., 9 cpd--equivalent to 20/67 Snellen acuity) might be sufficient for measuring NVG-aided contrast threshold for high spatial frequencies when a high amount of incompatible light is present.

It is recommended that a single NVG-aided CS assessment chart be designed for use in future research (both in the laboratory and in the field). As with the USAF Tri-Bar Chart, a single chart will be easier to use in the field and will decrease the amount of time required to make measurements. The chart should incorporate a number of spatial frequencies of varying contrast. For example, the chart could have four rows of 12, 9, 6, and 3 cpd spatial frequencies with each row having at least nine columns of decreasing contrast. An unaided CS chart similar to this design already exists (Vision Contrast Test System made by Vistech Consultants, Inc.), but the contrast ranges are not sufficient for NVG-aided assessment. A single chart with multiple spatial frequencies would allow for data collection over a wide variety of assessment conditions (e.g., aircraft that vary in the spectral transmission of their transparencies and their level of incompatible light). However, as with NVG-aided VA, an adequate sample size is needed to ensure that decision biases do not affect the measurements. NVG-aided CS charts, similar to the ones used in the present research, may need to be used if two subjects differ in reported contrast threshold.

Many subjects commented on the obvious degradation of the NVG image when the red light was in the NVG FOV. However, very few subjects commented on any obvious degradation of the NVG scene when the green light (small degradation condition) was present. From an operational perspective, many Air Force aircraft contain lights that are not fully NVG compatible or are in the process of being modified. Operators should be aware that cockpit lights that are not modified according to MIL-L-85762A criteria possibly can cause a slight degradation of NVG performance. A slight degradation is potentially more dangerous than a large degradation because it is imperceptible to the pilot. A cockpit lighting evaluation that does not include a measure of visual performance can fail to identify slightly incompatible lights, thus increasing the potential for NVG-related mishaps.

The green light degraded NVG-aided VA by 12% and NVG-aided CS (12 cpd) by 40%. In the past, researchers have used information regarding acuity loss to make inferences in an operational context. For example, given a 12% loss in resolution, one might conclude that an object normally identified at 5 miles without an incompatible light present may be visible only at 4.4 miles with an incompatible light illuminated. While this is a very general application, and other variables certainly impact NVG-aided target identification (e.g., ambient illumination, target reflectivity, scene contrast, weather, and spatial frequencies of an object), it does provide meaningful information to operators. Inferences to operational conditions have been made concerning measured loss in contrast during unaided viewing conditions. In the 1940s, research was undertaken to determine the distance at which camouflaged objects could be identified given the contrast of the object and the visibility in the atmosphere. The result was the development of nomographic visibility charts for different ambient illumination and target size conditions (Duntley, 1948). For example, given the following conditions: ambient illumination is 1.0 fL, atmospheric visibility is 9,000 yds, contrast of the target in question is 0.31, and size of the target is 100 sq ft, then the target is visible at 2,000 yds. Recently, computer models have been developed that predict the probability of correctly detecting an object given various environmental parameters (Gouveia, Hestand, Higgins, Olson, & Rubin, 1996). The use of these models, in combination with contrast data from cockpit lighting evaluations, may aid in determining the effect of incompatible light under operational conditions. Thus, a 40% degradation in contrast can be stated in terms that are operationally meaningful to pilots.

The results indicate that the modified Class B NVG is compatible with the current requirements defined in MIL-L-85762A. NVG-aided VA data reveal that 17 NVIS Green B warning indicators would need to simultaneously illuminate and be within the FOV of the NVG for degradation to occur. This is a highly unlikely occurrence. The NVG-aided VA data were obtained under a worst-case scenario (i.e., NVIS Green B warning light within the FOV of the NVG). The majority of NVIS-compatible cockpit light (e.g., general crew station lighting and primary and secondary instruments and panels) is NVIS Green A, which emits slightly less energy at 545 nm than NVIS Green B. Most cockpit light is normally illuminated to approximately 0.1 fL during NVG operations. The data obtained in this research indicate that at least 2,590 NVIS Green A lights would need to simultaneously illuminate and be within the FOV of the NVG for degradation to occur. Again, this is a highly unlikely occurrence. Therefore, when MIL-L-85762A is rewritten and updated, the current radiance requirements do not need modification to account for the added response of the modified Class B NVG at 545 nm.

CONCLUSION

Measurements of NVG-aided VA under incompatible light conditions revealed no significant differences between the USAF Tri-Bar Chart and the NVG Chart. Furthermore, NVG-aided CS was sensitive to negative effects from incompatible light and can be used to assess the compatibility of cockpit light. Incompatible light affected the contrast threshold for higher spatial frequencies more than for lower spatial frequencies. Finally, the modified Class B NVG is compatible with the current requirements defined in MIL-L-85762A for Class B NVGs. Thus, no new requirements need to be developed to address the modified Class B NVG filter in future cockpit lighting specifications.

REFERENCES

Antonio, J. C., & Berkley, W. E. (1993). Night vision goggle model F4949 preflight adjustment/ assessment procedures. (AL/HR-TR-1993-0111, AD A271 079). Mesa, AZ: Armstrong Laboratory, Aircrew Training Research Division.

Bryner, L. A. (1986). The effects of red cockpit lighting on night vision imaging systems (NVIS). (Report No. NADC 88121-50, AD-B130 479). Warminster, PA: Naval Air Development Center.

DeVilbiss, C. A., & Antonio, J. C. (1994). Measurement of night vision goggle (NVG) visual acuity with the NVG resolution chart. Aviation, Space, and Environmental Medicine, 65 (9), 846-850.

Duntley, S. Q. (1948). The visibility of distance objects. Journal of the Optical Society of America, 38, (3), 237-249.

Ginsburg, A. P., Easterly, J., & Evans D. W. (1983). Contrast sensitivity predicts target detection field performance of pilots. Proceedings of the Human Factors Society - 27th annual meeting, 269-273.

Ginsburg, A. P., Evans, D. W., Sekule, R., & Harp, S. A. (1982). Contrast sensitivity predicts pilots' performance in aircraft simulators. American Journal of Optometry and Physiological Optics, 59, 105-109.

Gouveia, M. J., Hestand, P. D., Higgins, G. J., Olson, S. H., & Rubin, S. L. (1996). Night vision goggles operations weather software (NOWS) user's manual. (TR-07611-3). Hanscom AFB, MA: Phillips Laboratory, Directorate of Geophysics.

Howard, C. M., & Burnidge, J. A. (1994). Colors in natural landscapes (AL/HR-TR-1993-0172). Mesa, AZ: Armstrong Laboratory, Aircrew Training Research Division.

Kruk, R., & Regan, D. (1983). Visual test results compared with flying performance in telemetry-tracked aircraft. Aviation, Space, and Environmental Medicine, 54, 906-911.

Kruk, R., Regan, D., Beverley, K. I., & Longridge, T. (1981). Correlations between visual test results and flying performance on the advanced simulator for pilot training (ASPT). Aviation, Space, and Environmental Medicine, 52, 455-460.

Kruk, R., Regan, D., Beverley, K. I., & Longridge, T. (1983). Flying performance on the advanced simulator for pilot training and laboratory tests of vision. Human Factors, 25(4), 457-466.

O'Neal, M. R., & Miller, R. E., II (1988). Further investigation of contrast sensitivity and visual acuity in pilot detection of aircraft. (AAMRL-TR-88-002), Wright-Patterson AFB, OH: Armstrong Aerospace Medical Research Laboratory.

Rabin, J. (1993). Spatial contrast sensitivity through aviator's night vision imaging system. Aviation, Space, and Environmental Medicine, 64, 706-710.

Rabin, J. (1995). Small letter contrast sensitivity: An alternative measure of visual resolution for aviation candidates. Aviation, Space, and Environmental Medicine, 66(1) 56-58.

Rabin, J., & McLean, W. (1996). A Comparison Between Phosphors for Aviator's Night Vision Imaging System. Aviation, Space, and Environmental Medicine, 67, 429-433.

Reetz, F., III (1987). Rationale behind the requirements contained in Military Specifications MIL-L-85762 and MIL-L-85762A. (Report No. NADC-87060-20) Warminster, PA: Naval Air Development Center.

Reising, J. D., Antonio, J. C., & Fields, B. (1996). Procedures for Conducting a Field Evaluation of NVG Compatible Cockpit Lighting. (AL/HR-TR-1995-0167). Mesa, AZ: Armstrong Laboratory, Aircrew Training Research Division.

Reising, J. D., Grable, C., Stearns, S. M., Craig, J. L., & Pinkus, A. R. (1995). Night vision imaging system lighting compatibility testing of a production C-130H3 aircraft. (AL/HR-TR-1994-0166). Mesa, AZ: Armstrong Laboratory, Aircrew Training Research Division.

Reising, J. D., Martin, J., & Berkley, W. E. (1996). Evaluation of modified Class B (HUD emission bandpass) night vision goggle filters. (AL/HR-TR-1995-0193). Mesa, AZ: Armstrong Laboratory, Aircrew Training Research Division.

Reising, J. D., Martin, E. L., & Gregory, M. (in process). The measurement and categorization of night vision goggle image halos. Mesa, AZ: Armstrong Laboratory, Aircrew Training Research Division.

Shapely, R., & Lam, K. D. (1993). Contrast Sensitivity. MIT Press: Cambridge, MA.