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Visual Acuity for High-Contrast Tri-bar Targets Illuminated with Spectra Simulating Night Vision Goggle (NVG) Displays and the No-moon Night Sky

by V. Grayson CuQlock-Knopp, Edward Bender, John Merritt, and Jennifer Smoot

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NOTICES

Disclaimers

Army Research Laboratory
Aberdeen Proving Ground, MD 21005

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14. ABSTRACT

This report presents two studies that measured unaided visual acuity using a 50-in square high-contrast U.S. Air Force (USAF) 1951 Tri-Bar chart viewed from 12 ft at luminance levels ranging from 0.00046 fL (much darker than a night vision goggle [NVG] display of an overcast starlight scene) to 21.5 fL (much brighter than a NVG display of a full-moon scene). To avoid visual noise artifacts, these studies did not use actual NVG displays. The studies were designed to support general modeling efforts at the U.S. Army Research Development and Engineering Command (RDECOM) Communications-Electronics Research Development and Engineering Center (CERDEC), Night Vision and Electronic Sensors Directorate (NVESD). For Study 1, the Tri-Bar chart was back-lit with a spectrum similar to the standard yellowish-green (P43) phosphor NVG display. In Study 2, the chart was back-lit with tungsten illumination, similar to a 2856 K blackbody spectrum. In addition to providing measures of unaided visual acuity, we introduced a new technique—the Green-appearance Scale—to determine the luminance levels at which participants transitioned from scotopic viewing of the Tri-Bar chart to mesopic viewing, and from mesopic viewing to photopic viewing. We describe this technique and present the data as part of the methodology and results of Study 1.

15. SUBJECT TERMS

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1. Introduction

Models designed to predict visual task performance when using night vision devices (NVDs) are predicated upon a given set of human-eye performance data for viewing imagery displayed at the typical luminance levels experienced when using NVDs. In the case of direct-view image-intensified (I^2) systems, such as night vision goggles (NVGs), the I^2 display imagery can range in luminance from several foot-lamberts (fL, equivalent to ~3.426 cd/m^2) under full-moon conditions to as little as 0.01 fL under overcast starlight conditions. One key parameter used in these models is visual acuity. Typically, for the assessment of visual acuity aided by NVGs, an observer views a high-contrast visual test chart through NVGs and his or her visual acuity, based on reading the chart, is recorded.[*] One noteworthy finding in this area is that when visual-acuity assessments were obtained across seven different laboratories using the same two NVGs (two pairs of intensifier tubes), a range of 0.41 cyc/mrad in visual acuity measurement was found (Task, 2001). Task attributed differences in visual acuity measurements, in part, to differences in the test charts and the testing procedures used for obtaining the assessments. Task and Pinkus (2007) and Capo´-Aponte, Temme, and Task et al. (2009) discuss a variety of other factors that interfere with reproducing NVG-aided visual acuity measurements for identical types of NVGs. An assessment of unaided visual acuity (direct view without NVGs) is needed to separate the performance of the NVGs from the limits of the human visual system alone.

The objective of the present series of studies was to fulfill the U.S. Army Research Development and Engineering Command (RDECOM) Communications-Electronics Research Development and Engineering Center (CERDEC), Night Vision and Electronic Sensors Directorate (NVESD) modelers' need for germane unaided-eye performance data obtained using high-contrast targets back-illuminated with (1) a spectrum simulating the yellowish-green P43 phosphor and (2) a spectrum simulating 2856 K blackbody illumination. Unaided-eye performance data were needed for both monocular and binocular viewing conditions and for a very wide luminance range from dimmer than any NVG display (0.005 fL) to the bright extreme of an NVG display (4.0 fL). In order to control for NVG display artifacts, it was particularly important in this series of studies to avoid the pronounced temporal noise scintillations that would have been present if visual acuity had been measured while looking through NVGs under the very dim no-moon conditions of the luminance range used in this report. The positions of the P43 phosphor, ~2856 K blackbody, and the filter used to simulate the P43 phosphor in the International Commission on Illumination (CIE) chromaticity diagram space are shown in figure 1.

[*] Task and Pinkus (2007) denote visual acuity assessed through the NVDs as "NVG-aided visual acuity."

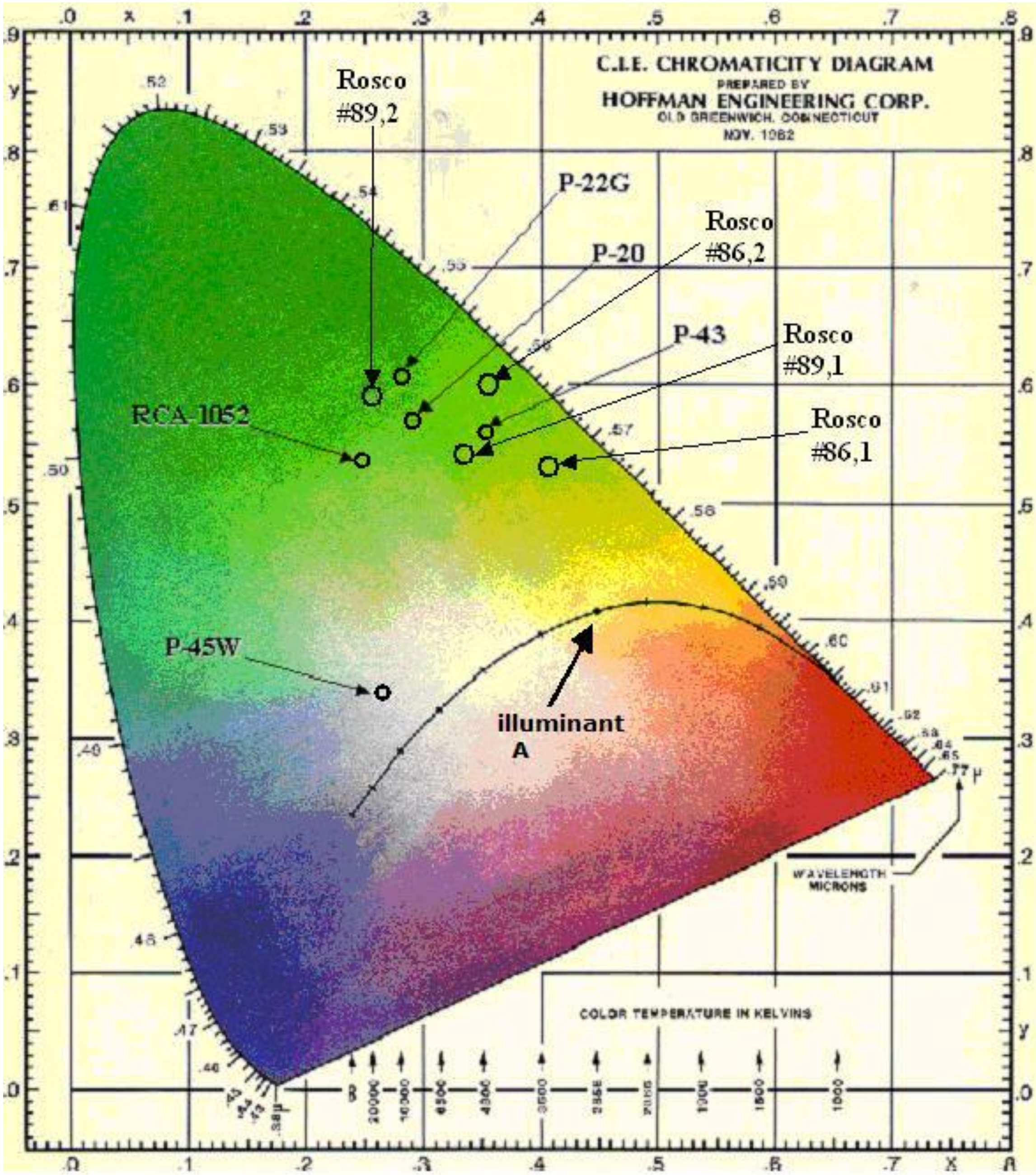

Figure 1. The position of P43 phosphor, ~2856 K blackbody, and the single layer moss-green filter (Roscolux #89,1), which is located adjacent to the P43 in CIE space. The ~2856 K blackbody is shown on the chart as CIE Illuminant A.

Study 1 of this report is also designed to introduce and apply a new metric for assessing the luminance level when participants transitioned from scotopic (rod cells only) viewing to mesopic (both rods and cones) viewing, and from mesopic viewing to photopic (cone cells only) viewing of a vision chart. This new metric is described in section 2 of this report.

2. Study 1: Visual Acuity for High-contrast Tri-Bar Targets Illuminated with a Spectrum Simulating a P43 Green-phosphor NVG Display

Study 1 was designed to support the NVESD modeling efforts by providing visual-acuity data for targets back-illuminated with a spectral content similar to the yellowish-green appearance of the typical P43 NVG. The study also introduced a new metric, the Green-appearance Scale, for measuring at what luminance levels observers transitioned from scotopic to mesopic to photopic viewing of the vision test chart.

2.1 Method

2.1.1 Target Chart

The experimenter measured the observer's high-contrast visual acuity using a large-size (50-in square) U.S. Air Force (USAF) 1951 Tri-Bar resolution chart, shown in figure 2. The Tri-Bar chart consists of six groups with six "elements" each diminishing in size steps of ~12%, with each element having three vertical bars and three horizontal bars. The six elements in each successive group are half the size of the elements in the preceding group. The Tri-Bar chart was chosen because it provides six small steps in target size between doublings, unlike most standard visual-acuity eye charts.

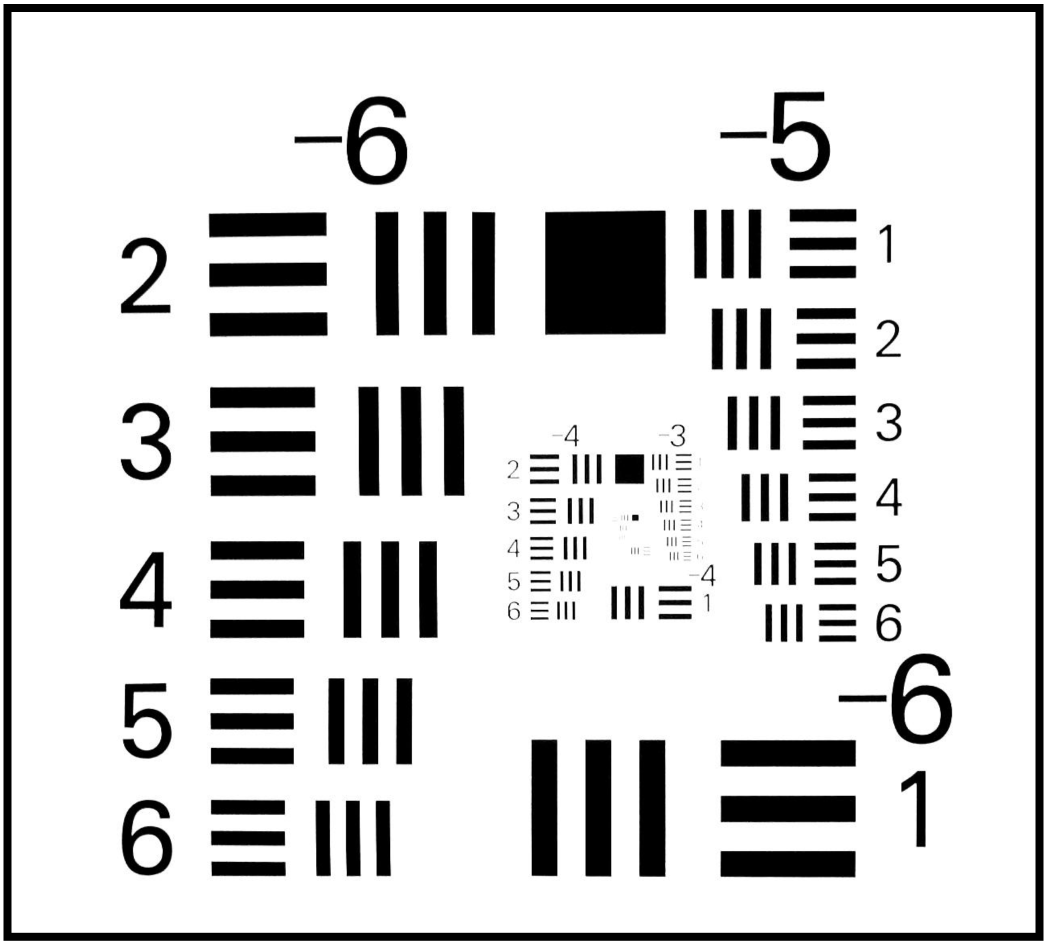

Figure 2. The USAF 1951 Tri-Bar resolution chart used in the study, 50 x 50 in.

2.1.2 The Green-appearance Scale

The Tri-Bar chart was back-illuminated through a green filter and appeared gray when viewed scotopically in very dim light. As luminance levels increased, first there was a barely noticeable green tint to the chart, followed by an increase in the saturation and brightness of the green as participants transitioned from mesopic to photopic vision. We developed the "Green-appearance Scale" shown in figure 3 as a means for encoding these transitions.

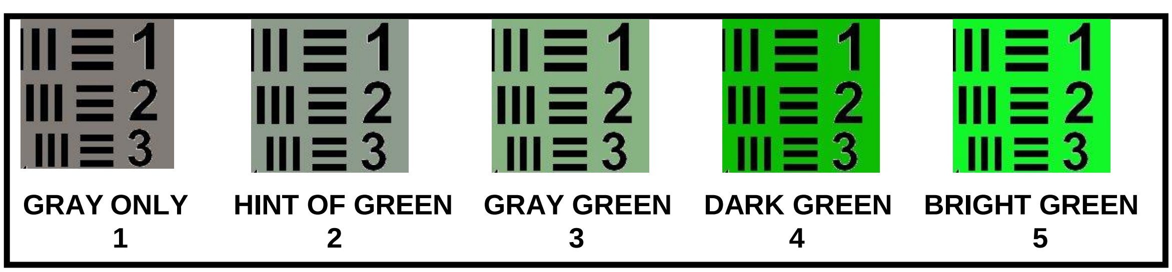

Figure 3. The Green-appearance Scale used to rate the appearance of the Tri-Bar chart at each luminance level.

We operationally defined scotopic luminance levels as a participant's rating of 1 ("gray only"), which indicated that the participant could not perceive even a slight hint of green in the target. A transition to mesopic vision was operationally defined as a rating of 2 (hint of green). The first indication of clearly seeing green (photopic vision) was operationally defined as a rating of 4.

2.1.3 Luminance Levels

Tri-Bar acuity data were collected over a range of luminance from 0.00046 to 21.5 fL, simulating NVG display luminance when viewing a scene that is much darker than overcast starlight to a scene much brighter than a full-moon scene. After photometric analysis for similarity to typical NVG display phosphors in common use, the following green filter was selected to provide green illumination for the USAF 1951 Tri-Bar chart. Acuity testing spanned a range of light levels typical of NVG display luminance, with additional levels above and below to determine the behavior of the curve at the upper and lower ends of the NVG range. Table 1 shows the 15 steps of target luminance that were used, and the rough correspondence to natural scene conditions for both aided viewing (i.e., using NVG) and unaided (naked eye) viewing. To simulate viewing the chart with P43 NVGs, we used one layer of the Roscolux #89 Moss Green filter, indicated on the CIE chart in figure 1 as Roscolux #89,1. Appendix A provides other pertinent information about this Moss Green filter. The green filter covered the back of the entire back-illuminated Tri-Bar chart to produce a spectrum similar to the standard yellowish-green (P43) phosphor.

Table 1. The luminance levels used in Studies 1 and 2, with descriptive equivalents.

Levels	fL	Unaided-Eye Luminance Condition	NVG Display Luminance Condition
15	21.5	~ Sunrise/sunset	Small lighted areas in scene
14	10		
13	4.64		
12	2.15		~ Full moon
11	1	~ High extreme of twilight	~ ¼ moon
10	0.464		
9	0.215		
8	0.1	~ Deep twilight	~ Starlight
7	0.0464		
6	0.0215		
5	0.01	~ Full moon	~ Overcast starlight
4	0.00464		
3	0.00215		
2	0.001	~ ¼ moon	~ NVG no-input background
1	0.00046		

2.1.4 Luminance-level Apparatus

The Tri-Bar chart was placed in a 50-in square opening in the wall between two rooms. In the room behind the Tri-Bar chart, a fixture holding an array of incandescent tungsten light bulbs of various wattages provided an adjustable backlight approximating the spectral composition of a 2856 K blackbody.

To avoid changes in color temperature, dimmers were not used. Instead, the experimenter precisely controlled the luminance level steps by turning on or off combinations of switches to obtain the 15 repeatable luminance levels with a large variety of incandescent light bulbs that were running at their design voltage (120 V AC). The luminance produced by this apparatus was continuously monitored using a sensitive radiometer fitted with a remote photopic-luminance head aimed at a blank section in the center of the front of the chart, and recorded for every trial. The paper Tri-Bar chart was back-illuminated to achieve maximum contrast of the Tri-Bar chart elements when viewed by the participant in the darkened room on the front side of the chart.

2.1.5 Photometric Equipment

To ensure accurate measures of target luminance at the very low levels, the photometer used in this study was a Model IL-1700 Research Radiometer, purchased from International Light in Peabody, MA. This instrument had National Institute of Standards and Technology (NIST) traceability and was capable of measurements over a wide dynamic range, with excellent linearity from 5.8 E-6 fL up to 5.8 E+3 fL, using a High Gain Detector (SHD033) with a photopic Y filter and R luminance barrel. The radiometer's photopic-luminance head was positioned on the front side of the Tri-Bar chart for continuous monitoring of target luminance, which was recorded for each trial group/element reading.

2.2 Participants

Thirty-one Industrial Engineering students from Morgan State University, Baltimore, MD, served as participants. These participants were between 18 and 30 years of age. All participants had a minimum of 20/30 visual acuity (corrected or uncorrected) in both eyes, with normal color vision and stereoscopic depth perception.

2.3 Procedures

The participant began the study by reading and signing a consent form. The participant was then screened to ensure the visual requirements were met. Prior to a 30-min dark adaptation period, the participant was given instructions on how to report the acuity level in terms of the group and element number on the Tri-Bar chart. Information related to this training appears in appendix B. The experimenter then confirmed the participant's ability to read the Tri-Bar chart by pointing to various group and element numbers and asking the participant to name them correctly. This process continued until the participant gave six consecutive correct answers. Next, the experimenter illustrated the full range of the Green-appearance scale by showing the participant how the Tri-Bar chart looked at all the luminance levels.

The participant was then seated facing the Tri-Bar chart so that the center of the Tri-Bar chart was perpendicular to the participant's line of sight. The participant sat 12 ft from the chart, a viewing distance selected so that the width of the smallest bars on the chart (Group -1/Element 6) subtended 0.53 min of arc, corresponding to 20/11 acuity. Next, the participant adapted to the dark for 30 min. The experimenter, due to dark adaptation considerations, presented the experimental conditions in ascending order of luminance. In other words, the experimenter started at the lowest luminance level and worked upwards to the highest luminance level.

To complete the Tri-Bar task in this experiment, the participant reported the smallest group and element number where he or she could distinctly see the element's three horizontal or vertical bars. The participant was trained to report the smallest element size where the three horizontal or vertical bars could be seen as separate bars (the "see as three" criterion, not just seeing the orientation of the *group* of three bars). Since the participant already knew the orientation of all target elements, this was a "trained observer" procedure, relying on the participant to make a judgment as to the smallest element that was just barely distinguishable as three separate bars.

For each trial, the participant first reported the smallest discernable group and element number using the left eye only, then stated the smallest discernable group and element number viewing the chart with the right eye only, and finally the participant stated the smallest discernable group and element number viewing the chart with both eyes (binocularly). The experimenter recorded these responses along with the actual fL luminance level in effect for each trial. The participant then gave the Green-appearance Scale rating when viewing the chart with both eyes. The experimenter then turned on the combination of lights that produced the next higher luminance level. Again, the participant gave the left-eye, right-eye, and binocular acuity responses, plus the Green-appearance Scale rating. The experimenter continued this process until the participant had given the last binocular acuity response and the last Green-appearance Scale rating at the highest luminance-level condition.

2.4 Results

Data points for all 15 luminance levels are shown graphically in figure 4. This graph depicts the left-eye, right-eye, and binocular acuity for the 47,000 to 1 range of luminance viewed with the green filter. Error bars are not provided on the graph because the data points are too close together for legibility. Instead, the standard deviation and mean for each data point for each viewing condition and luminance level are provided in table 2. (This graph/table format is followed for all acuity data presented in this report.) The data points covering the decades of primary interest (¼ moon, full-moon, deep twilight, high extreme of twilight, and sunrise or sunset) are highlighted in yellow in table 2[†].

[†]In the tables, the P43 illumination is denoted as "green."

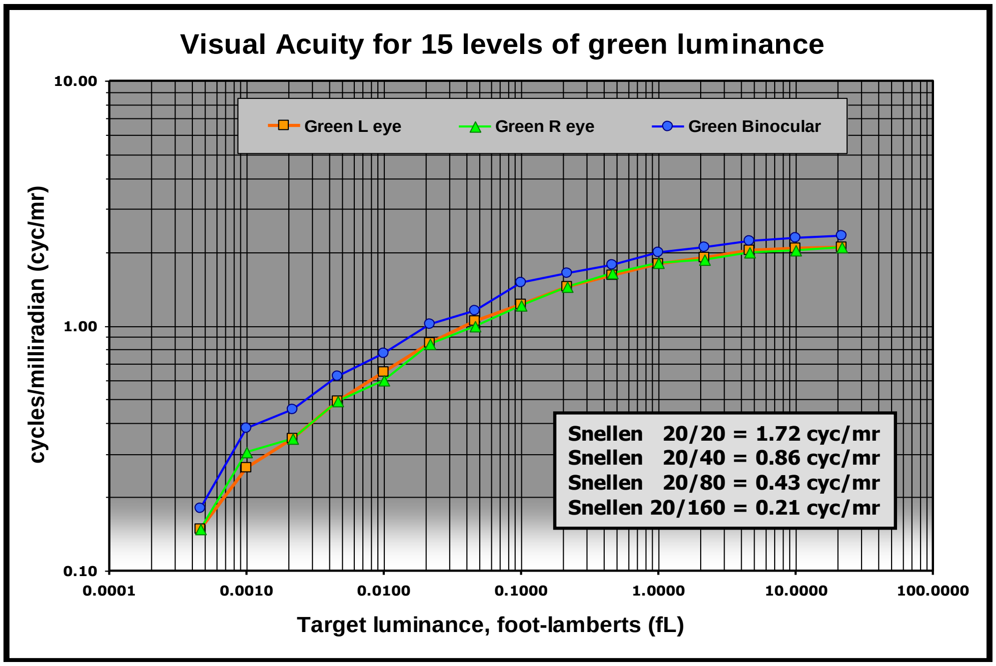

Figure 4. Tri-Bar acuity as a function of luminance level for the green-phosphor simulation. Higher numbers are better acuity.

Table 2. The means and standard deviations of the P43 visual acuity scores (in cycles per milliradian) for the left (L)-eye, right (R)-eye, and binocular viewing of the Tri-Bar chart at all 15 luminance levels.

Levels	fL	Unaided-Eye Luminance Condition	NVG Display Luminance Condition	Green L-eye Means	Green L-eye Std. Dev.	Green R-eye Means	Green R-eye Std. Dev.	Green Binocular Means	Green Binocular Std. Dev.
15	21.5000	~Sunrise/sunset	Small lighted areas in scene	2.0977	0.7813	2.0989	0.8050	2.3345	0.7110
14	10.0000			2.0727	0.7899	2.0236	0.7877	2.2843	0.7329
13	4.64000			2.0258	0.7902	1.9943	0.7723	2.2085	0.7320
12	2.15000		~Full moon	1.9007	0.7431	1.8664	0.7827	2.0962	0.6764
11	1.00000	~High extreme of twilight	~¼ moon	1.7822	0.7772	1.8078	0.8014	1.9968	0.6897
10	0.46400			1.6122	0.7949	1.6369	0.8251	1.7756	0.8142
9	0.21500			1.437	0.7916	1.436	0.7708	1.6394	0.7743
8	0.10000	~Deep twilight	~Starlight	1.2221	0.7338	1.2131	0.7165	1.5055	0.7550
7	0.04640			1.0441	0.7824	0.9991	0.7132	1.1572	0.6642
6	0.02150			0.8477	0.3627	0.8402	0.3632	1.0111	0.7289
5	0.01000	~Full moon	~Overcast starlight	0.6495	0.3144	0.599	0.1948	0.7702	0.2957
4	0.00464			0.4929	0.1927	0.4922	0.1900	0.6227	0.2189
3	0.00215			0.346	0.1402	0.3474	0.1758	0.4539	0.1990
2	0.00100	~¼ moon	~NVG no-input background	0.2621	0.3214	0.3056	0.3756	0.3800	0.4340
1	0.00046			0.1485	0.0520	0.148	0.0489	0.1806	0.0583

2.5 Green-appearance Scale

For each luminance level, the percentages of each of the 31 participants that made each of the 5 ratings on the Green-appearance Scale are given in table 3. These percentages are represented graphically in appendix C. The majority of the participants began to notice a hint of green at 0.00464 fL. The majority of participants clearly perceived color at 0.464 fL.

Table 3. The percentages of each of the 31 participants that made each of the five ratings on the Green-appearance scale for each luminance level.

Levels	fL	Unaided-Eye Luminance Condition	NVG Display Luminance Condition	Gray Only %	Hint of Green %	Gray-Green %	Dark Green %	Bright Green %
15	21.5000	~Sunrise/sunset	Small lighted areas in scene	0	0	6.5	3.2	90.3
14	10.0000			0	0	6.5	12.9	80.6
13	4.64000			0	0	6.5	19.4	74.2
12	2.15000		~Full moon	0	3.2	6.5	38.7	51.6
11	1.00000	~High extreme of twilight	~¼ moon	0	6.5	12.9	61.3	19.4
10	0.46400			0	9.7	29.0	58.1	3.2
9	0.21500			0	16.1	54.8	25.8	3.2
8	0.10000	~Deep twilight	~Starlight	3.2	19.4	64.5	12.9	0
7	0.04640			3.2	41.9	45.2	9.7	0
6	0.02150			12.9	58.1	19.4	9.7	0
5	0.01000	~Full moon	~Overcast starlight	19.4	61.3	19.4	0	0
4	0.00464			45.2	48.4	6.5	0	0
3	0.00215			71.0	29.0	0	0	0
2	0.00100	~¼ moon	~NVG no-input background	83.9	16.1	0	0	0
1	0.00046			100	0	0	0	0

A second objective of this project was to provide data for the same 15 luminance levels using targets back-illuminated with tungsten illumination approximating a 2856 K blackbody spectral composition. This data collection is described next as Study 2, followed by a discussion of both studies.

3. Study 2: Visual Acuity for High-contrast Tri-bar Targets Illuminated with a Spectrum Simulating a 2856 K Display

Study 2 was designed to support NVESD modeling efforts by providing visual acuity data for targets back-lit with a spectrum approximating 2856 K blackbody illumination.

3.1 Method

3.1.1 Participants

Sixteen of the 31 Morgan participants who completed Study 1 participated again in Study 2. The participants were between 18 and 30 years of age. All participants had a minimum of 20/30 acuity (corrected or uncorrected) in both eyes, with normal color vision and stereoscopic depth perception. The selection of the subset of 16 was based exclusively on the experimenter's ability to locate the original participants, assumed to be a random selection process‡.

In addition to recalling a subset of 16 of the original 31 participants, four NVESD subject-matter experts (SMEs), between the ages of 35 and 52, were included in this data collection. These four participants were tested prior to testing the 16 Morgan participants. The NVESD participants had a minimum of 20/30 acuity (corrected or uncorrected) in both eyes, with normal color vision and stereoscopic depth perception. Their data are reported here separately from the data from the Morgan participants because of potential differences that could be attributable to age or experience in reading Tri-Bar charts.

All procedures and apparatus for Study 2 were the same as in Study 1, except that the green filter behind the Tri-Bar chart was removed. The chart was back-lit with the same tungsten-bulb apparatus, approximating the spectral composition of 2856 K blackbody illumination.

3.1.2 Results

Figure 5 presents a graph of the left-eye, right-eye, and binocular acuity for all 15 luminance levels for the 16 Morgan participants viewing the Tri-Bar chart with no filter (the 2856 K-display simulation). Table 4 provides the means and standard deviations for the unaided visual acuity data using the 2856 K display for all luminance levels for the 16 Morgan participants who completed Study 2. In the tables, the 2856 K illumination is denoted as "white."

‡There is no reason to believe that our ability to locate any given participant would be related to his or her visual acuity.

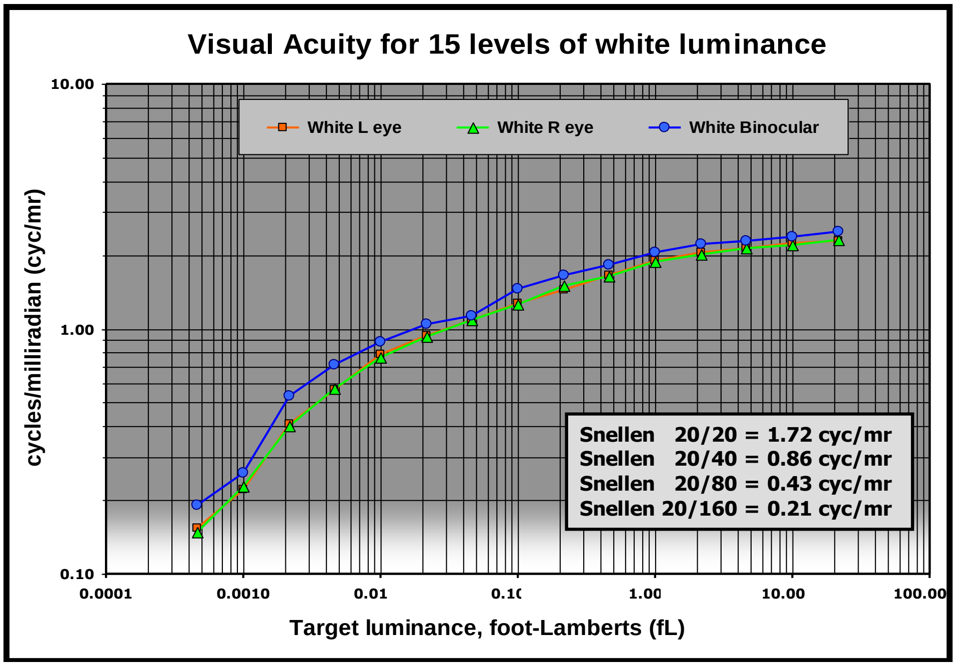

Figure 5. Tri-Bar acuity as a function of luminance level for the 2856 K display simulation for the 16 Morgan participants.

Table 4. The means and standard deviations of the visual acuity for the L-eye, R-eye, and binocular viewing of the Tri-Bar chart at all 15 luminance levels for the 2856 K illumination for the 16 Morgan participants.

Levels	fL	Unaided-Eye Luminance Condition	NVG Display Luminance Condition	White L-eye Cyc/mr	L-eye Std. Dev. (White)	White R-eye Cyc/mr	R-eye Std. Dev. (White)	White Binocular Cyc/mr	Binocular Std. Dev. (White)
15	21.5000	~Sunrise/ sunset	Small lighted areas in scene	2.2741	0.4852	2.3071	0.3919	2.5038	0.4632
14	10.0000			2.2439	0.4885	2.2055	0.4590	2.3833	0.4499
13	4.64000			2.1429	0.5096	2.1242	0.5043	2.2768	0.4911
12	2.15000		~Full moon	2.0498	0.4586	2.0097	0.4789	2.2123	0.4698
11	1.00000	~High extreme of twilight	~¼ moon	1.8887	0.4665	1.8745	0.4677	2.0607	0.4438
10	0.46400			1.648	0.4126	1.6429	0.4398	1.8298	0.4246
9	0.21500			1.4402	0.4389	1.5045	0.4723	1.6558	0.4351
8	0.10000	~Deep twilight	~Starlight	1.2708	0.4120	1.2629	0.3693	1.4615	0.4637
7	0.04640			1.0835	0.3314	1.0897	0.3141	1.1268	0.4411
6	0.02150			0.9402	0.2968	0.9276	0.3310	1.0438	0.3554
5	0.01000	~Full moon	~Overcast starlight	0.7854	0.2849	0.7632	0.2839	0.8886	0.3702
4	0.00464			0.5645	0.3242	0.5718	0.3267	0.7136	0.3515
3	0.00215			0.4096	0.3712	0.3991	0.3675	0.5318	0.3946
2	0.00100	~¼ moon	~NVG no-input background	0.2209	0.0714	0.2279	0.0893	0.2581	0.0764
1	0.00046			0.1545	0.0479	0.1479	0.0435	0.1906	0.0816

Figure 6 shows the binocular acuity over the wide range of luminance used for both the green-display simulation in Study 1 and the white luminance of Study 2. Table 5 shows the binocular visual acuity means and standard deviations for or the P43 green simulation and 2856 K "white" viewing conditions. Figure 7 shows the corresponding monocular acuity scores for the left and right eyes. These graphs are included to allow the reader to compare acuity scores between the green versus 2856 K displays[§].

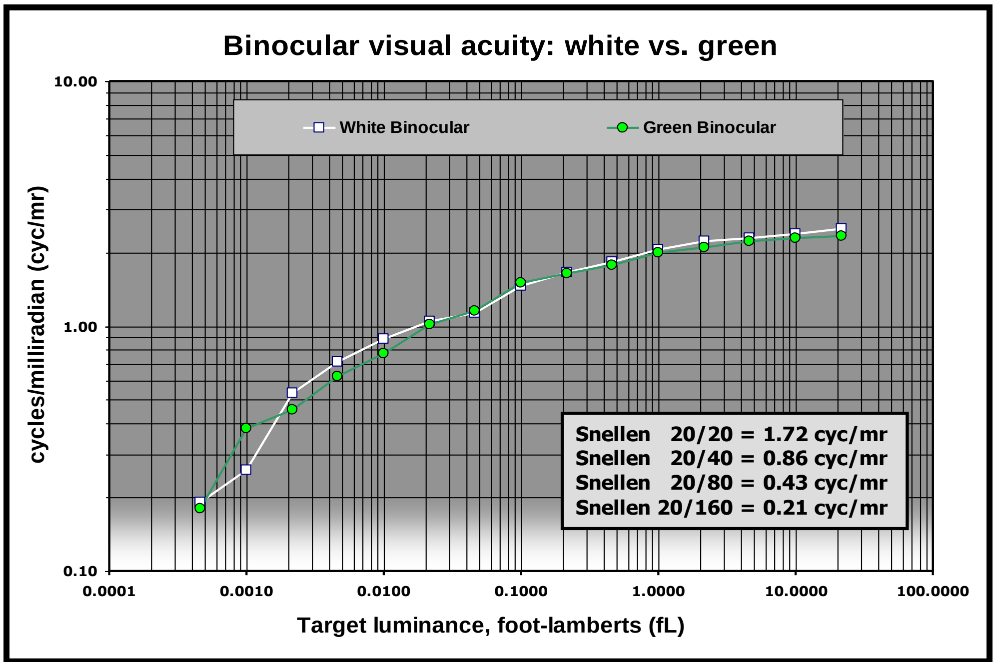

Figure 6. Tri-Bar acuity as a function of luminance level for binocular, green (31 Morgan) and white (16 Morgan participants) illumination.

[§] Recall that the "white" display is the 2856 K blackbody illumination shown as illuminant A in figure 1. Note that P45 white phosphor (the typical phosphor in white-phosphor NVGs) is not in the same position in CIE space.

Table 5. The binocular visual acuity means (in cycles per milliradian) and standard deviations for or the P43 green simulation (original 31 Morgan participants) and 2856 K "white" viewing conditions (subset of 16 Morgan participants).

Levels	fL	Unaided-Eye Luminance Condition	NVG Display Luminance Condition	Green 1 Cyc/mr	Binocular Std. Dev. (Green)	White 2 Cyc/mr	Binocular Std. Dev. (White)
15	21.5000	~Sunrise/sunset	Small lighted areas in scene	2.3345	0.711004	2.5038	0.463154
14	10.0000			2.2843	0.732863	2.3833	0.44993
13	4.64000			2.2085	0.732048	2.2768	0.491087
12	2.15000		~Full moon	2.0962	0.676354	2.2123	0.469794
11	1.00000	~High extreme of twilight	~¼ moon	1.9968	0.689741	2.0607	0.443813
10	0.46400			1.7756	0.814189	1.8298	0.424559
9	0.21500			1.6394	0.774312	1.6558	0.435108
8	0.10000	~Deep twilight	~ Starlight	1.5055	0.754992	1.4615	0.463724
7	0.04640			1.1572	0.664232	1.1268	0.441114
6	0.02150			1.0111	0.728885	1.0438	0.355417
5	0.01000	~Full moon	~ Overcast starlight	0.7702	0.295696	0.8886	0.370205
4	0.00464			0.6227	0.218913	0.7136	0.351495
3	0.00215			0.4539	0.198999	0.5318	0.394648
2	0.00100	~¼ moon	~ NVG no-input background	0.3800	0.434036	0.2581	0.07639
1	0.00046			0.1806	0.058339	0.1906	0.081638

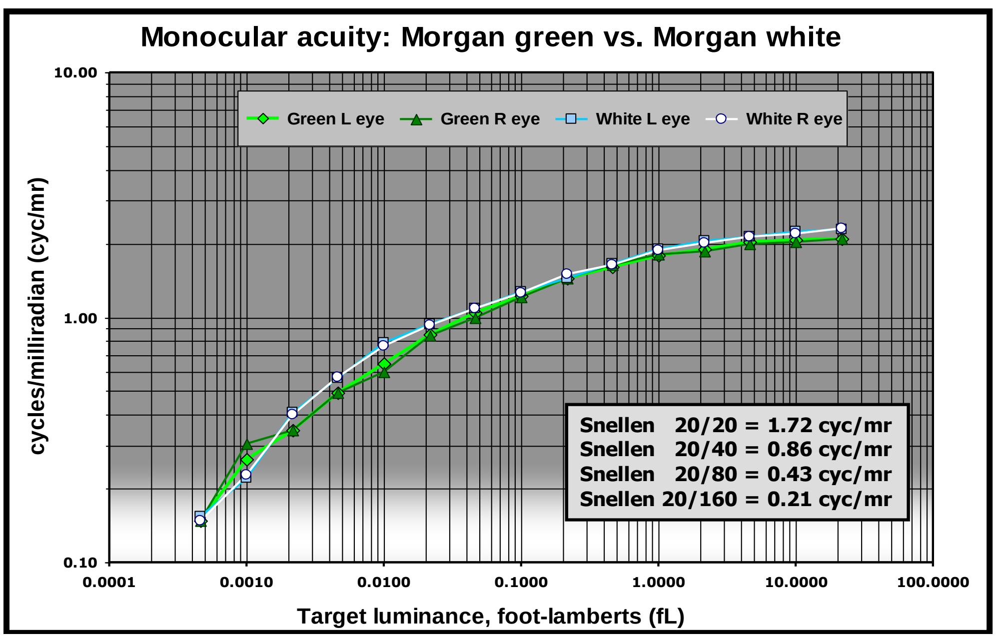

Figure 7. Tri-Bar acuity data as a function of luminance level for monocular left-eye and right-eye, 2856 K white-display and green-display illuminations.

3.2 NVESD Versus Morgan for the White Illumination

The results of the visual-acuity measurements for the four NVESD participants compared with the 16 Morgan participants are given in figures 8 and 9. These graphs indicate small but consistent differences in average acuity scores between the older NVESD participants and the college-age Morgan participants. Means and standard deviations for the NVESD participants are also provided in table 6 (binocular) and table 7 (monocular).

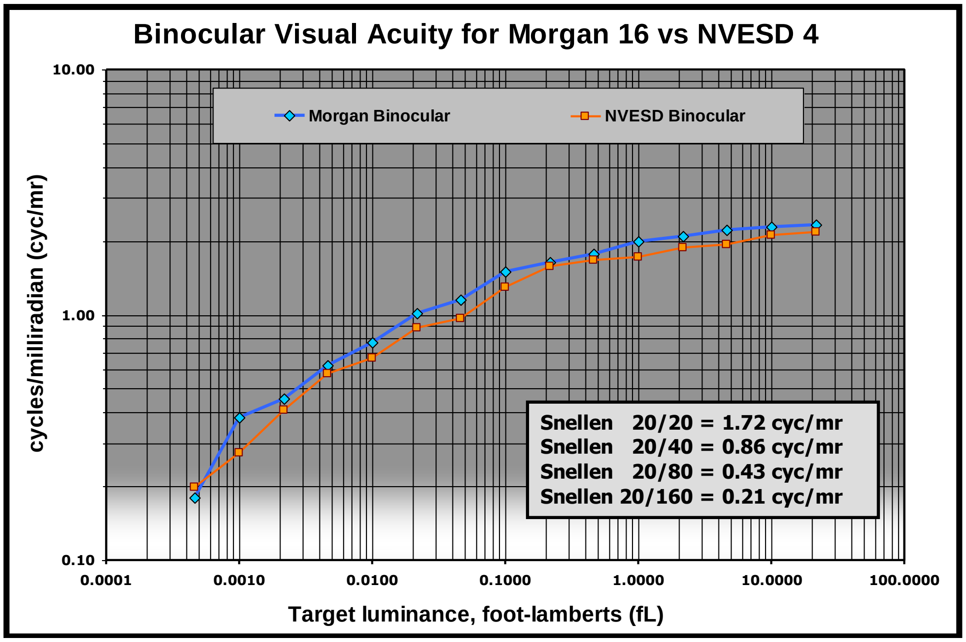

Figure 8. Binocular Tri-Bar acuity as a function of luminance level for the college-age Morgan and the older NVESD participants.

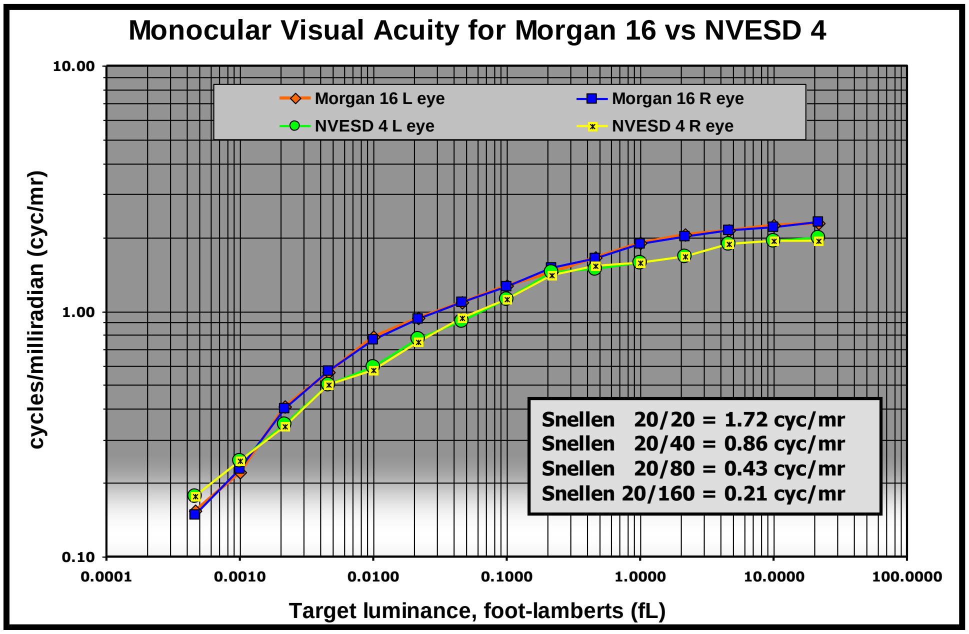

Figure 9. Left-eye and right-eye Tri-Bar acuity as a function of luminance level for the Morgan and the NVESD participants.

Table 6. The luminance levels, means, and standard deviations of the binocular visual acuity for the white lighting conditions of the four NVESD participants.

Levels	fL	Unaided-Eye Luminance Condition	NVG Display Luminance Condition	NVESD White Cyc/mr	Binocular Std. Dev.
15	21.5000	~Sunrise/sunset	Small lighted areas in scene	2.165493	0
14	10.0000			2.106429	0.118129
13	4.64000			1.929235	0
12	2.15000		~Full moon	1.876614	0.105241
11	1.00000	~High extreme of twilight	~¼ moon	1.718753	0
10	0.46400			1.671873	0.093759
9	0.21500			1.578114	0.093759
8	0.10000	~Deep twilight	~Starlight	1.293818	0.140714
7	0.04640			0.96784	0.091266
6	0.02150			0.885687	0.052621
5	0.01000	~Full moon	~Overcast starlight	0.663483	0.037208
4	0.00464			0.57836	0.086047
3	0.00215			0.407527	0.044322
2	0.00100	~¼ moon	~NVG no-input background	0.273301	0.041987
1	0.00046			0.198621	0.030016

Table 7. The light levels, means, and standard deviations of the monocular visual acuity for the white lighting conditions of the four NVESD participants.

Levels	fL	Unaided-Eye Luminance Condition	NVG Display Luminance Condition	NVESD White L-eye Cyc/mr	L-eye Std. Dev. (White)	NVESD White R-eye Cyc/mr	R-eye Std. Dev. (White)
15	21.5000	~Sunrise/sunset	Small lighted areas in scene	1.9883	0.118129	1.929235	0
14	10.0000			1.929235	0	1.929235	0
13	4.64000			1.876614	0.105241	1.876614	0.105241
12	2.15000		~Full moon	1.671873	0.093759	1.671873	0.093759
11	1.00000	~High extreme of twilight	~¼ moon	1.583229	0.170706	1.578114	0.093759
10	0.46400			1.48947	0.08353	1.531235	0
9	0.21500			1.447705	0.096452	1.40594	0.08353
8	0.10000	~Deep twilight	~Starlight	1.119512	0.120707	1.119512	0.120707
7	0.04640			0.911997	0.060761	0.941529	0.106417
6	0.02150			0.768175	0.072438	0.747292	0.084463
5	0.01000	~Full moon	~Overcast starlight	0.591097	0.033149	0.57633	0.062681
4	0.00464			0.50354	0.095396	0.50354	0.095396
3	0.00215			0.347395	0.070827	0.340818	0.083982
2	0.00100	~¼ moon	~NVG no-input background	0.245646	0.050082	0.245646	0.050082
1	0.00046			0.176952	0.026741	0.176952	0.026741

3. Conclusions

To support NVESD modeling efforts, this study was designed to collect data on unaided visual acuity as a function of a large range of luminance levels for two different spectral compositions. For Studies 1 and 2, the acuity tasks were designed to eliminate the visual noise that is typical of NVG displays at low light levels. For Study 1, the chart was back-lit with 2856 K blackbody tungsten illumination passed through a green filter. For Study 2, the green filter was removed so the chart was back-lit only with 2856 K blackbody tungsten illumination. We also introduced a new technique—the Green-appearance Scale—to determine the luminance level at which participants transitioned from scotopic viewing of a Tri-Bar chart to mesopic viewing, and from mesopic viewing to photopic viewing. For each luminance level, data points are provided representing the mean visual acuity scores (averaged across the participants) for L-eye, R-eye, and binocular viewing. Our objective was to provide descriptive data to the NVESD, rather than a data summary that would include inferential statistics.

One general comment about these data-collection activities is that the Tri-Bar chart and methodology used in these studies depends on an honest and consistent assessment from a "trained observer" as to the smallest element that was just barely distinguishable as three separate bars. We attempted to motivate the participants during the experimental-overview process about the importance of honest responses, and we believe we were successful. A verifiable method, however, would be preferred to allow the experimenter to confirm each participant's performance. Future research will address this issue by using a test chart with Sloan characters (Ricci, Cedrone, and Cerulli, 1998). A test chart with Sloan characters requires a participant to identify the letters correctly, allowing the experimenter to verify the participant's accuracy.

This study provides acuity data for observers viewing a Tri-Bar chart with luminance conditions simulating the P43 green-phosphor and luminance conditions simulating a 2856 K display. The 2856 K simulation was not intended, however, to provide the basis for an acuity comparison for P43 green-phosphor versus P45 white-phosphor displays. To address a comparison of these two phosphors, we conducted a study to examine the effect of phosphor type (white versus green) on visual acuity across a range of illumination conditions created using neutral density (ND) filters placed over the eyepieces of actual NVGs. This ND-filter approach allowed us to avoid the increasing scintillation and noise that is typical of current NVG displays operating in low luminance conditions. This study is described in a separate report (currently under review) comparing P43 and P45 phosphors.

4. References

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Ricci, F.; Cedrone, C.; Cerulli, L. Standardized Measurement of Visual Acuity. *Ophthalmic Epidemiology* **1998**, *5* (1), 41–53.

Task, H. L. Night Vision Goggle Visual Acuity Assessment: Results of an Interagency Test. *Proceedings of the SPIE- The International Society of Optical Engineering: Helmet- and Head-Mounted Displays VI*, 4361, 2001, 130–137.

Task, H. L.; Pinkus, A. R. Theoretical and Applied Aspects of Night Vision Goggle Resolution and Visual Acuity Assessment. *Proceedings of the SPIE- The International Society of Optical Engineering: Helmet- and Head-Mounted Displays Xll*, 6557, 2007, 1–11.

Appendix A. Moss Green Filter Information

After photometric analysis for similarity to typical NVG display phosphors in common use, the following green filter was selected to provide green illumination for the USAF 1951 Tri-Bar chart.

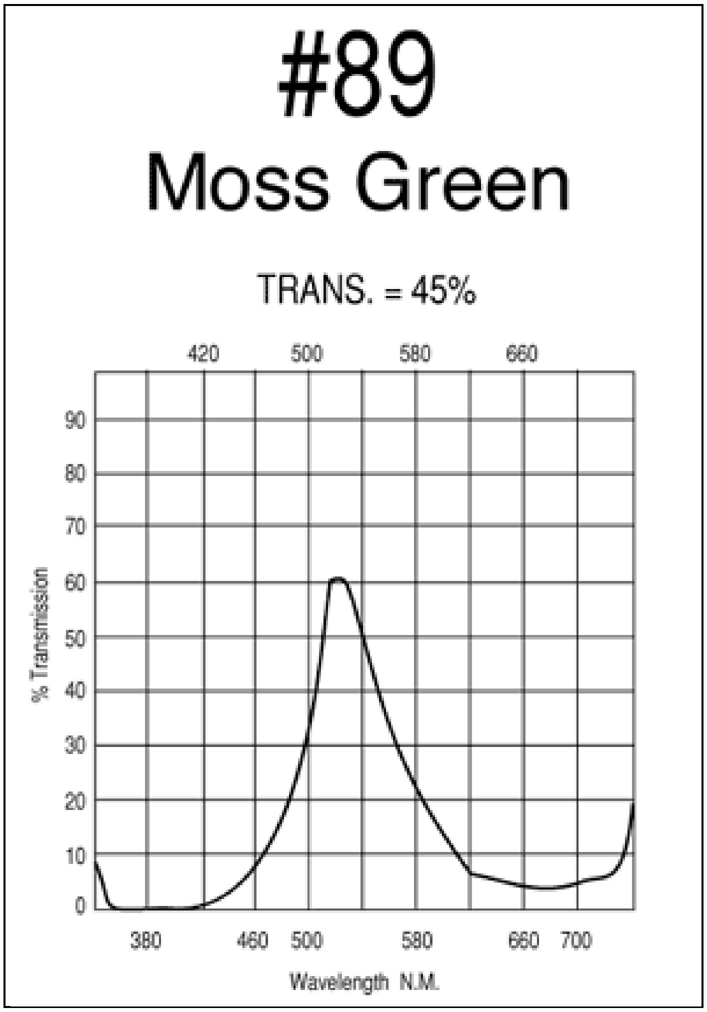


Figure A-1. Spectral plot for the Roscolux #89 Moss Green filter.

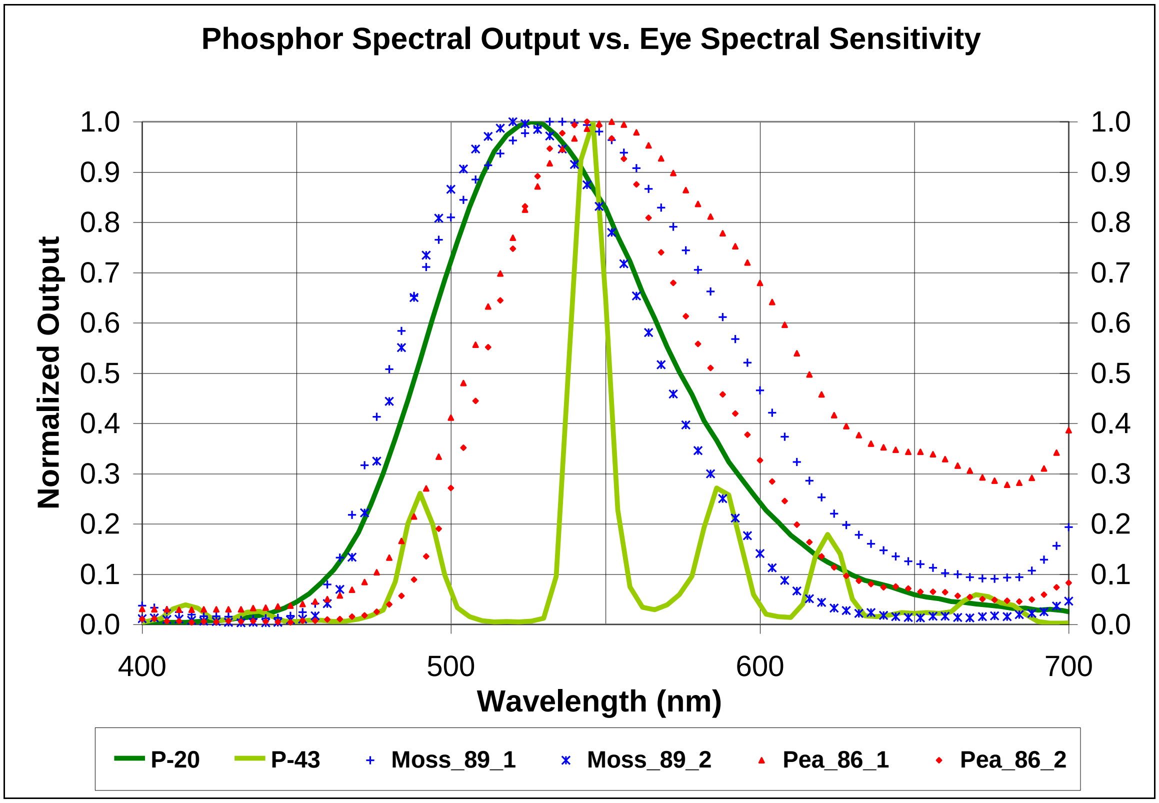
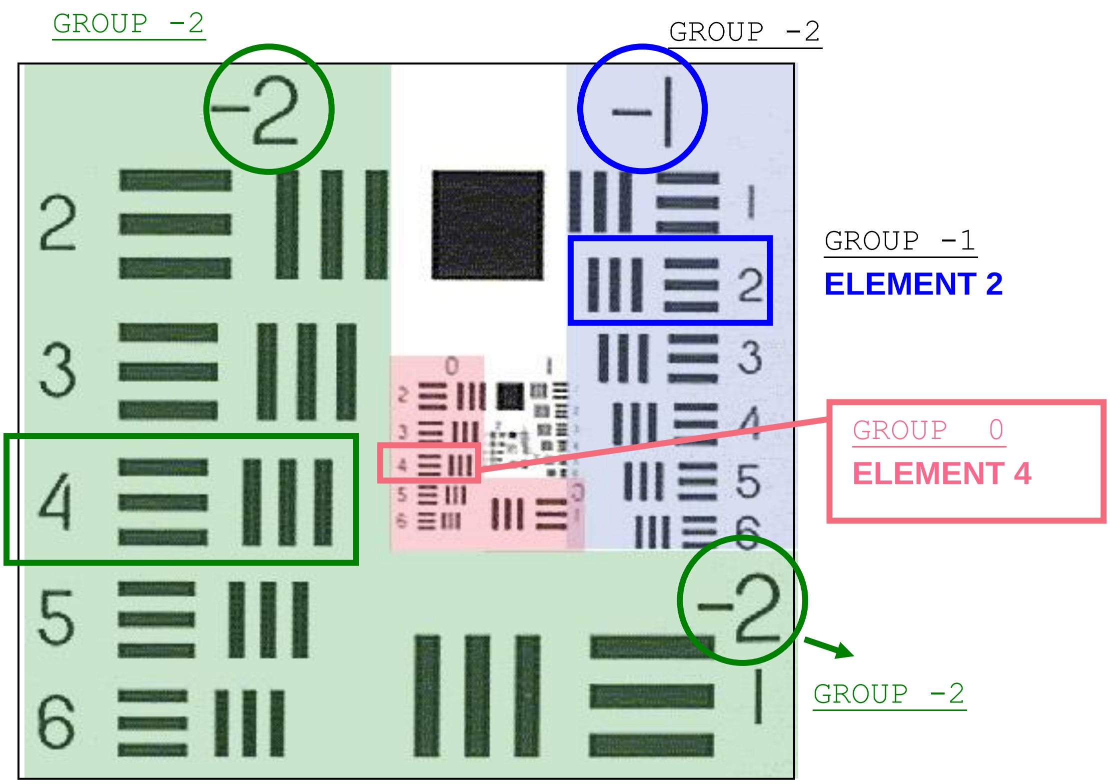


Figure A-2. Composite spectral plots for typical NVG phosphors and the Roscolux filter emulators, in both single- and dual-layer configurations.

Appendix B. Tri-Bar Instructions**

To complete this study, you will be seated in this chair and will be required to state the smallest element that you can read on this chart, which is called a Tri-Bar chart. To complete this task, you must state the smallest element size where the three horizontal and vertical bars can be seen as three separate bars. Report the smallest set you can see-as-three, not just the smallest set where you can see the orientation of the group of three bars.

I will now demonstrate how to name the group and element number.



Now I need to check your understanding of how to read the Tri-Bar chart. I will point to an element and you are to state the group and element number. (The participant was required to get six consecutive answers correct.) Now you are ready to begin the study. You first need to adapt to the dark for 30 min. Then for each trial you will report the smallest discernable group and element number using the left-eye only, then the right-eye only, and finally using both eyes.

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Appendix C. Graphical Representation of Percentages

Figure C-1 offers a graphical representation of the percentage of participants providing a rating for each luminance level and rating category.

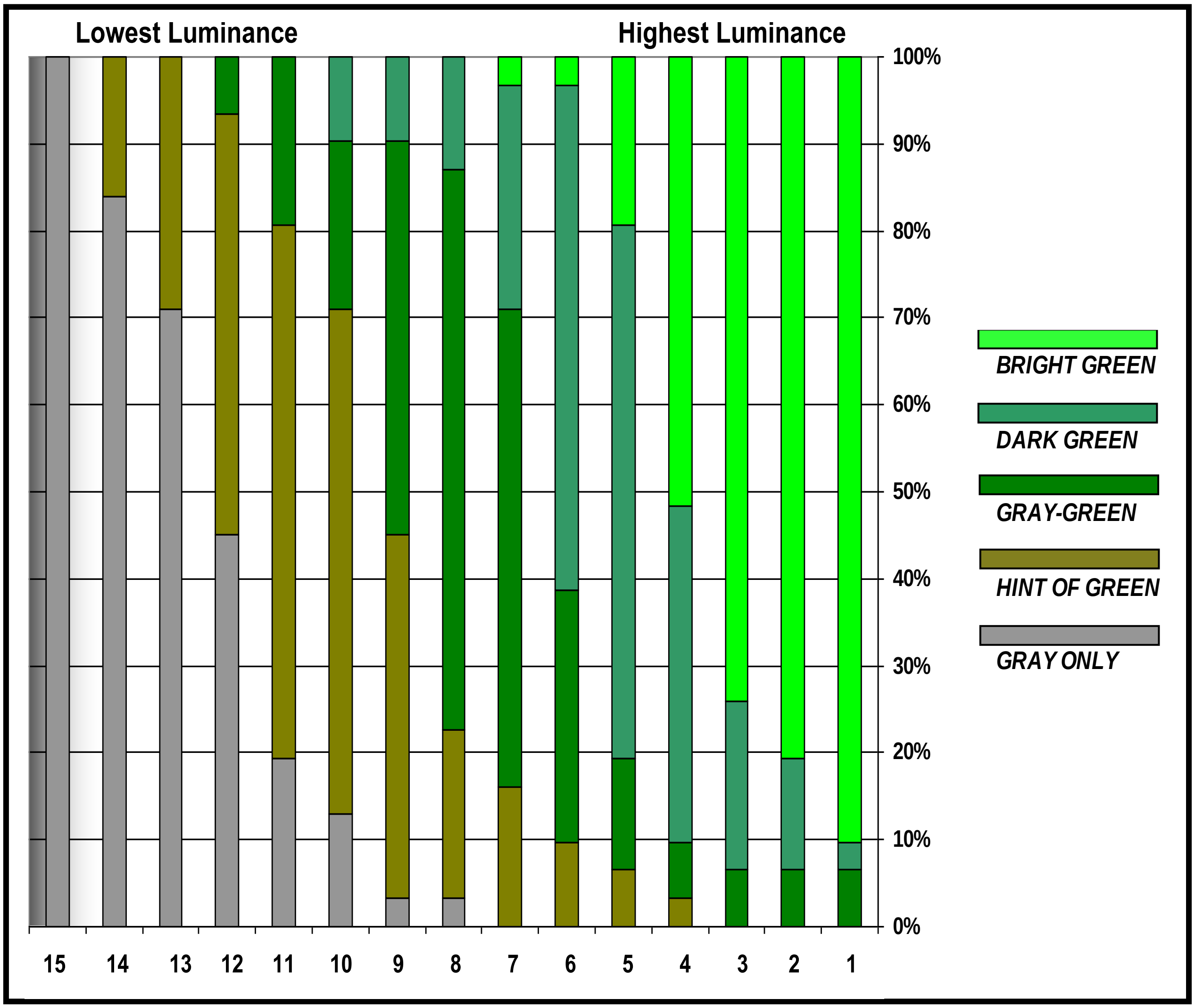

Figure C-1. Percentage of participants providing a rating for each luminance level and rating category.

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List of Symbols, Abbreviations, and Acronyms

CERDEC	Communications-Electronics Research Development and Engineering Center
CIE	International Commission on Illumination
I^2	image-intensifier
ND	neutral density
NIST	National Institute of Standards and Technology
NVDs	night vision devices
NVESD	Night Vision and Electronic Sensors Directorate
NVGs	night vision goggles
RDECOM	Research Development and Engineering Command
USAF	U.S. Air Force

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