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UNITED STATES ARMY AEROMEDICAL RESEARCH LABORATORY

Exploratory Detection and Identification of Small Colored Circles under Low Light Conditions for Unaided and Aided Vision

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14. ABSTRACT

Night vision goggle (NVG) compatibility assessment of carry-on medical equipment for airworthiness release (AWR) certification for use in the UH-60 Black Hawk revealed possible visual signatures that could compromise mission security and increase the vulnerability of crew and aircraft. This limited sample, exploratory study sought to estimate the detection ranges of illuminated targets unaided and under NVGs. The goal of this study was to develop methods to measure and quantify carry-on medical equipment visual signatures in the laboratory, and correlate the laboratory measurements and different light units with the visual detection data of known targets. Findings suggest there is much more variability in scotopic detection ranges among observers than best acuity values. This study indicates the greatest detection ranges would most likely be under starlight. Methods to mitigate target luminance and signature for medical carry-on equipment in the visual and near IR spectrum should be explored. In addition to filters and placement within the aircraft, simple, readily available materials to cover the equipment when on the ground or during take-off and landings might be effective. The U.S. Army Aeromedical Research Laboratory also developed a method to more accurately estimate central and peripheral viewing detection under starlight illumination from the photopic light measurements and the scotopic to photopic ratio.

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Summary

Night vision goggle (NVG) compatibility assessment of carry-on medical equipment for airworthiness release (AWR) certification for use in the UH-60 Blackhawk revealed possible visual signatures that could compromise mission security and increase the vulnerability of crew and aircraft. Equipment visual signatures were viewable from outside the aircraft at night, both unaided and with night vision devices.

We identified two important issues. The first issue relates to how aircraft compatible lighting is determined; typically, a spectral radiometer that only determines radiance and not target size is used. This is an issue because detection range is proportional to target dimensions. Second, previous methods of measuring light sources in candela units for viewing in low-light (*scotopic* vision) and low, but not quite dark light levels (*mesopic* vision) do not consider the changes in spectral sensitivity caused when the eye transitions from light to dark and back to light (the Purkinje shift). During this transitional period, or the Purkinje shift, the eye becomes more sensitive to shorter wavelengths; blues appear brighter and reds appear darker (Editor, N.D.). As will be discussed in this report, candela is not the preferred unit of measurement for detection under dim ambient conditions such as starlight. Color and/or the *scotopic* to *photopic* ratio is a major factor in central versus peripheral vision detection where the shorter visual spectrum targets have more peripheral vision sensitivity (Hansen, Pracejus, & Gegenfurtner, 2009). Our research suggests that both direct viewing and peripheral detection are important for tactical observations.

This exploratory, limited sample study sought to estimate the detection ranges in starlight or lower light levels using well-defined targets of size and intensity unaided and under NVGs. The goal of this study was to develop methods to measure and quantify carry-on medical equipment visual signatures in the laboratory, and correlate the laboratory measurements and different light units with the visual detection data of known targets.

Findings suggest there is much more variability in *scotopic* detection ranges among observers than best acuity values. Color and/or the *scotopic* to *photopic* ratio is a major factor in central versus peripheral vision detection where the shorter visual spectrum targets have more peripheral vision sensitivity (Hansen et al., 2009). This study indicates the greatest detection ranges would most likely be under starlight.

This study also found that the mini iPad 3, similar tablets, or smart phones could be used to measure and quantify visual signatures for carry-on equipment in a laboratory setting. These devices display colored circular targets of different diameters from 13 to 832 pixels (1 to 64 mm) at a near constant luminance values from indicated battery charge from 100 to 30 percent (%) or lower. The aided detection device used in the field detection studies was a Gen III, OMNIBUS V issued AN/PVS-14 monocular night vision device (MNVD). Carry-on medical equipment emitting light sources vary considerably in size and lighting components, would be difficult to quantify with any current measuring methods.

This study suggests methods to mitigate target luminance and signature for medical carry-on equipment in the visual and near IR spectrum should be explored. In addition to filters and placement within the aircraft, simple, readily available materials to cover the equipment when on the ground or during take-off and landings might be just as effective as expensive NVG compatible filters. Because of this research, the U.S. Army Aeromedical Research Laboratory (USAARL) developed a method to address this issue; it estimates both central and peripheral viewing detection under starlight illumination from the *photopic* light measurements and the *scotopic* to *photopic* ratio.

Background

The assessment of NVG compatibility of carry-on medical equipment for AWR certification for use in the UH-60 Blackhawk revealed possible visual signatures. Equipment visual signatures were viewable from outside the aircraft at night, both unaided and with night vision devices. The most applicable reference for detection of luminance sources at night is a United States Coast Guard manual COMDTINST M1651.2A—*Aids to navigation Signal Design Manual (United States Coast Guard, 2002).*

Non-secure lighting (visible and near infrared) in an aircraft can generate visual signatures (aided and unaided) that compromise location and presence and increase vulnerability. The current method to determine aircraft compatible lighting uses a spectral radiometer that only determines radiance and not target size. MIL-STD-3009—*Lighting, Aircraft, Night Vision Imaging System [NVIS] Compatible* uses values of 0.67 sea-mile candela for the threshold detection of illuminance when there is no background lighting (U.S. Department of Defense, 2001). For our target detection models, both unaided and aided, we use different light units than the candela, which will need to be converted to target area times luminance and/or contrast. With the symbol Φv for lumen, Lv for candela and Ω for the angular span in steradians (sr), the relation is $\Phi v = Lv \cdot \Omega$. A steradian is $(180/\pi)^2$ or about 3282.8 square degrees. For an angular span of 360 degrees from the light source, 1 candela is 12.57 lumens (4* π). As a frame of reference, a standard 100 watt (W) bulb is rated at approximately 1600 lumens (lm) or 127 candelas (U.S. Department of Defense, 2001).

Whereas, target detection is based on both the target luminance/contrast and the area or size of the target in a given background luminance and complexity. Apparent light intensities drops off as the square of the viewing distance. For example, doubling the target intensity results in detection of the square root of two or 1.414 times the original detection distance. Likewise, the detection range is propositional to the target dimensions. For example if the target doubles in width and height (Area = 4x), the target can be seen twice as far away, assuming no loss in aerial transmission. Currently, we are evaluating the visual signature at night of the carry-on medical equipment located in the rear cabin on the floor and litter by using Soldiers located 75 meters (m) away from the side and front 45 degree quadrant of the aircraft.

As a result, USAARL identified two important issues. The first issue relates to how aircraft compatible lighting is determined; typically, a spectral radiometer that only determines radiance and not target size is used. This is an issue since detection range is proportional to the target dimensions. Second, previous methods of measuring light sources in candela units for viewing in low-light (*scotopic* vision) and low, but not quite dark light levels (mesopic vision) do not consider the changes in spectral sensitivity caused when the eye transitions from light to dark and back to light (the Purkinje shift). During the Purkinje shift, the eye becomes more sensitive to the shorter wavelengths causing blues to appear brighter and to reds appear darker (Editor, N.D.). Color and/or the *scotopic* to *photopic* ratio is a major factor in central versus peripheral vision detection where the shorter visual spectrum targets have more peripheral vision sensitivity (Hansen et al., 2009). (U.S. Department of Defense, 2001)Our research suggests that both direct viewing and peripheral detection are important for tactical observations.

This limited sample, exploratory study sought to estimate the detection ranges of illuminated targets unaided and under NVGs to more accurately develop methods to measure and quantify carry-on medical equipment visual signatures. The goal of the study is to correlate laboratory measurements and different light units with visual detection data for known targets in order to better quantify the night signature issues of medical carry-on equipment.

The report discusses detection-calculated methods, target characteristics variables such as luminance photopic and scotopic, color, differences in central and peripheral vision detection, differences in dark adaptation detection, etc. Ultimately, this research should drive mitigation factors to preserve mission capability and reduce vulnerability of people and equipment in operational environments.

Methods

The objective of this study was to estimate the detection ranges with unaided and NVG of illuminated targets under starlight or lower light levels using well-defined targets of size and intensity. The goal of this study was to be able to develop measuring methods to quantify carry-on medical equipment visual signatures in the laboratory, and correlate the laboratory measurements and different light units with visual detection data of known targets. The study took place in three phases: Phase 1—Laboratory Measurements; Phase 2—Indoor Subjective Detection Ranges of Targets; and Phase 3— Field Subjective Detection Ranges of Targets with Natural Vision and Monocular Night Vision Goggle.

Subjects

Six active duty military personnel under 36 years of age with 20/20 distant vision were recruited from USAARL.

Equipment

iPad Mini 3

Some exploratory assessments by the principal investigator (PI) indicated that the iPad Mini 3 can display colored circular targets of different diameters from 13 to 832 pixels (1 to 64 millimeters [mm]) at a near constant luminance values from indicated battery charge from 100 to 30 percent (%) or lower.

Monocular Night Vision Device

The aided detection device used in the field detection studies was a Gen III, OMNIBUS V issued AN/PVS-14 monocular night vision device (MNVD).

Light Measurement Devices

Photo Research1980A photometer and a PR735 spectral radiometer to determine both luminance (photopic and scotopic) in candelas/m2 or foot-lamberts (fL) (and NVIS radiance [W cm-2 sr-1]).

Light Measurement Tests

The luminance gains (foot-lambert (fL) output/ fL input) of the OMNI V, AN/PVS-14s MNVD to be used for Phase 3 field study were measured in the laboratory using a Hoffman Night Vision Goggle Test Set 126A.

Tests

The most applicable reference for detection of luminance sources at night is MIL-STD-3009 (U.S. Department of Defense, 2001). The manual uses values of 0.67 sea-mile candela for the threshold detection of illuminance when there is no background lighting. For our target detection models, both unaided and aided, we use different light units than the candela, which will need to be converted to target area times luminance and/or contrast. Using the equation:

$$\Phi v = Lv * \Omega$$

Where lumens are represented by Φv, candelas by Lv, and the angular span steradians by

Ω. A steradian is $(180/\pi)^2$ or about 3282.8 square degrees. For an angular span of 360 degrees from the light source, 1 candela is 12.57 lumens (4* π). As a frame of reference, a standard 100 watt (W) bulb is rated at approximately 1600 lumens (lm) or 127 candelas (U.S. Department of Defense, 2001). As will be discussed in this report, candela is not the preferred unit of measurement for detection under dim ambient conditions such as starlight.

Phase 1—Laboratory Measurements:

The iPad Mini 3 colored circular targets and medical carry-on equipment were measured and scanned with a Photo Research1980A photometer and a PR735 spectral radiometer to determine both luminance (*photopic* and *scotopic*) in candelas/m^2 or foot-lamberts (fL) (and NVIS radiance [W cm-2 sr-1]). The iPad Mini 3 colored targets were measured over time as the battery level dropped from 100% to less than 30%.

Phase 2—Indoor Subjective Detection Ranges of Selected iPad Mini 3 Targets Under Light Levels Below the Instrument Measuring Capabilities.

In the USAARL basement, storage room T-4, with a useable range from 3 to 20 meters (m), all internal lights were extinguished and light leaks around the doors sealed. The range was marked off in 1 m increments on the floor using fluorescent star symbols, which were activated with an ultraviolet light between trials. The iPad was mounted on a tripod at one end. The participating Soldiers were allowed to adapt to the darkness for 5 minutes, and then started the practice trials. The participant began viewing the iPad with a small circular target (1 or 2 mm diameter) of a given size and color (red, green, blue, white) at a range where the circular target could not be detected. For illustration purposes, Figure 1 shows the 102 pixel or 8 mm diameter jpeg colored circles displayed on the mini iPad used in the field study.

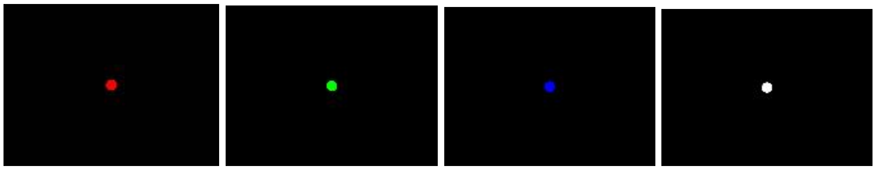


Figure 1. Colored detection targets displayed on iPad Mini 3 mini.

A small dim blinking (1 second on, 1 second off) red LED was positioned approximately ¾ m to the left of the iPad for orientation and fixation cue. The participant stepped towards the iPad in one step increments (½ m), stopping for about 8 seconds and responding with each step until they were sure they could see the target circle using direct foveal fixation. This was the start point, but the distance was not recorded. The participants then stepped back in one-step increments until they reported the target was not seen looking directly at it. This was the first data point recorded. Using the staircase method, they then stepped forward until they reported seeing it continuously with direct view for at least 3 seconds. This was data point two. After three trials (six data points) with direct view, the subject repeated the trials for each color using peripheral vision detection. The PI or assistant using a red flashlight behind the subject and not within view of the participant recorded each distance. The practice trial consisted of one target size and all four colors. The data collecting trails started after the practice trial and at least 30 minutes after the participant began dark-adapting. Each color and target size used 6 trials for each participant starting and finishing with the color white. The presentation sequence of the colors red, green, and blue, were balanced between subjects. Six subjects volunteered.

Phase 3—Field Subjective Detection Ranges Of Ipad Mini 3 Targets With Natural Vision And With A Current Monocular Night Vision Goggle.

The location on Fort Rucker was a narrow road between trees greater than 150 m in a secluded part of the military fort, away from cultural lighting. The distances to the target iPad were marked in 10 m increments using orange tags that can be seen within 5 m unaided under starlight conditions with the dark adapted vision. The data recorder determined the number of paces away from or towards the iPad targets from each 10 m distance or assistant Trials began 1 hour after sunset under starlight ambient illumination with clear skies, using the same procedures as the laboratory detection phase. The target size was 8 mm aperture covering the iPad to block all iPad background luminance.

For the NVG aided detection trails, a red 8 mm target was used since the detection of all of the other sizes and colors with the MNVD can be calculated (size x luminance/contrast is a constant). Because of the possible MNVD gain up to 15000 times the unaided vision, a NVG compatible filter for colored displays was added over the iPad to reduce target near IR radiance.

The same six volunteers assigned to USAARL that were used in Phase 2 detection study in the USAARL storage room participated in the field study. The sequences of the three colors of the targets were balanced for the six subjects for unaided vision in the laboratory and field detection assessments.

Results

Phase 1—Laboratory Measurements

Figure 2 shows the consistency of the luminance of the circular targets on the iPad with changing levels of battery charge for the white, red, and blue targets. Display luminance was adjusted to the minimum setting with no NVG compatible filter. The measurements were also made at the maximum luminance setting and showed the same luminance vs battery charge and color coordinance results as at the lowest level.

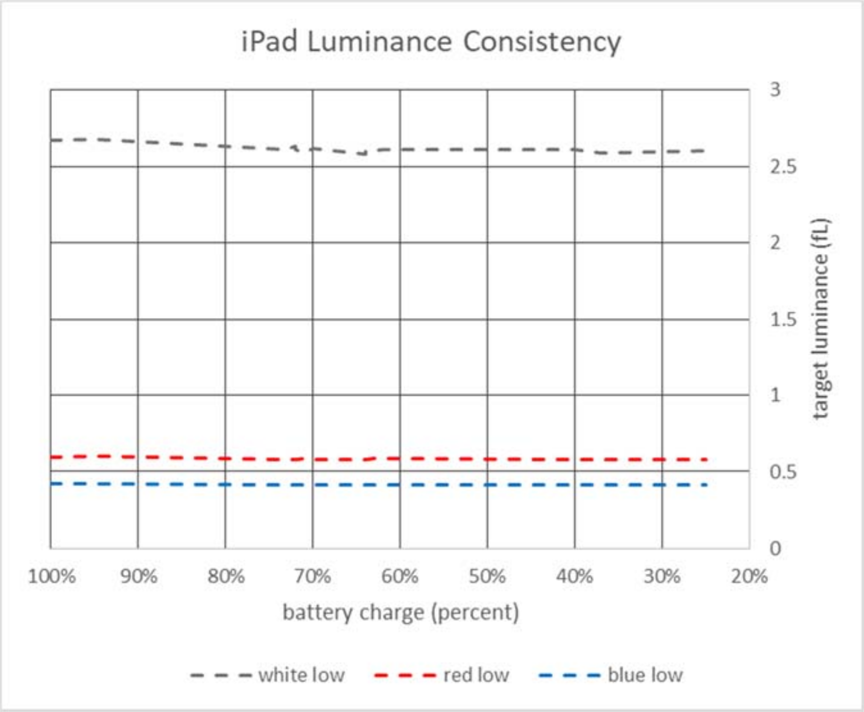


Figure 2. Luminance consistency with battery charge at the lowest display setting.

The iPad Mini 3 target luminances for *photopic* and *scotopic* vision were calculated from the Pritchard 735 spectrophotometer scans. To understand the spectral scans as related to visual sensitivity for light (*photopic*) and dark (*scotopic*) adaptation, Figure 3 shows the visual *photopic* and *scotopic* sensitivity curves. The shift in spectral sensitivity with increased dark adaptation from light adaptation is called the Purkinje shift (Editor, N.D.). The rods are insensitive to red wavelengths, and the fovea has very few blue cone receptors. The relevance of the *photopic* and *scotopic* luminance measurements for detection at night for red, green, blue, and white light with the unaided eye for foveal and peripheral vision is elaborated in the discussion section.

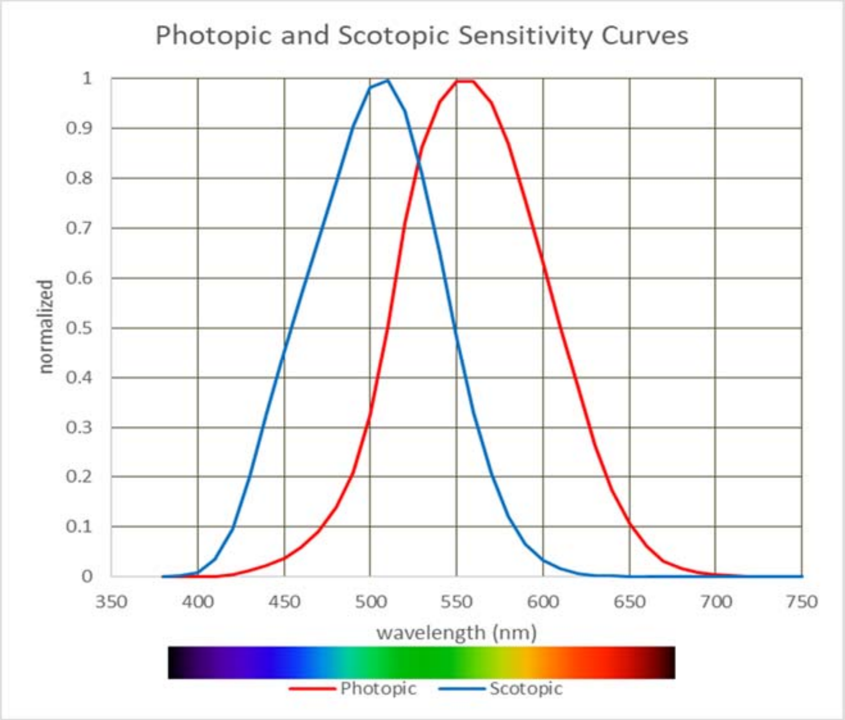


Figure 3. Photopic and *scotopic* sensitivity curves with associated colors.

Figure 4 shows the relative radiance spectral scan for the red, green, and blue (RGB) circular targets on the iPad Mini 3 and the photopic sensitivity curve (dashed). The white target plot would be the sum at each wavelength of the RGB spectrums.

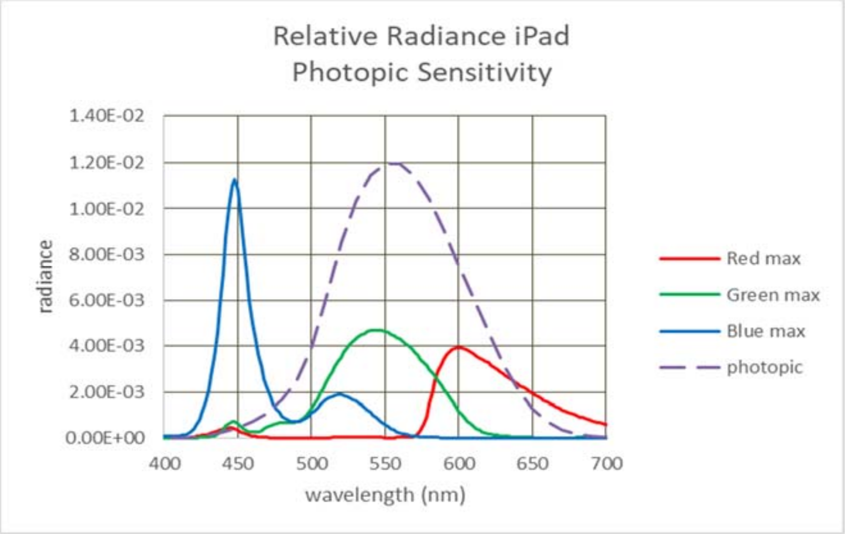


Figure 4. iPad RGB spectral scans and photopic sensitivity curve.

Figure 5 shows the resultant calculated photopic sensitivity to the RGB iPad targets. The photopic curves are calculated by multiplying the normalized photopic sensitivity curve for each wavelength times the RGB spectral data. Note the photopic sensitive for the RGB targets shows the eye most sensitive to green, followed by red and blue least.

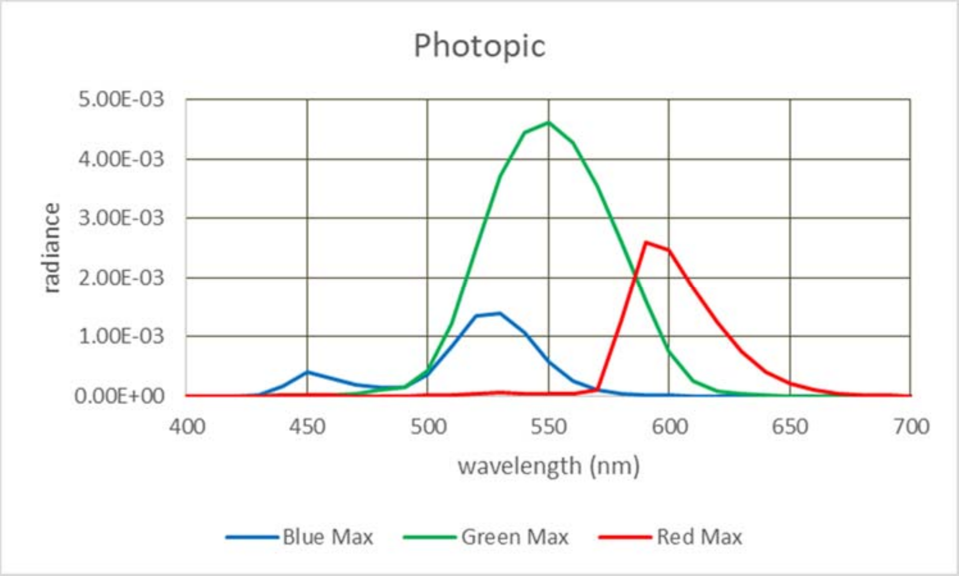


Figure 5. iPad Mini 3 spectral scans and *photopic* sensitivity curve.

Figure 6 shows the iPad RGB spectral scans and scotopic sensitivity curve (dashed).

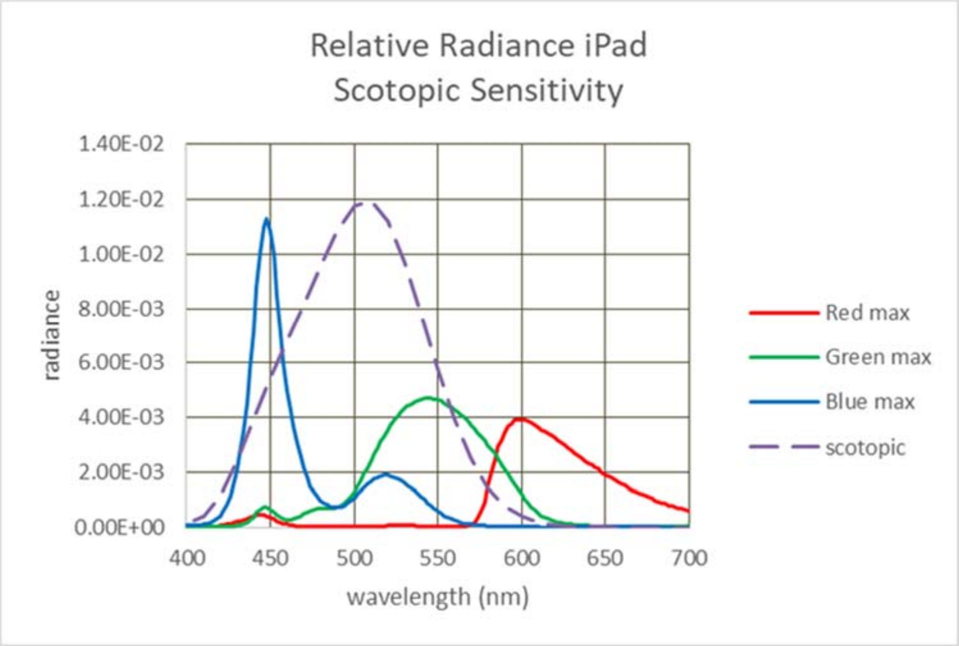


Figure 6. iPad RGB spectral scans and scotopic sensitivity curve.

Figure 7 shows the calculated scotopic curves for the iPad RGB components RGB that produced the white appearing targets. Note that scotopic vision is more sensitive to blue, followed by green, and least red.

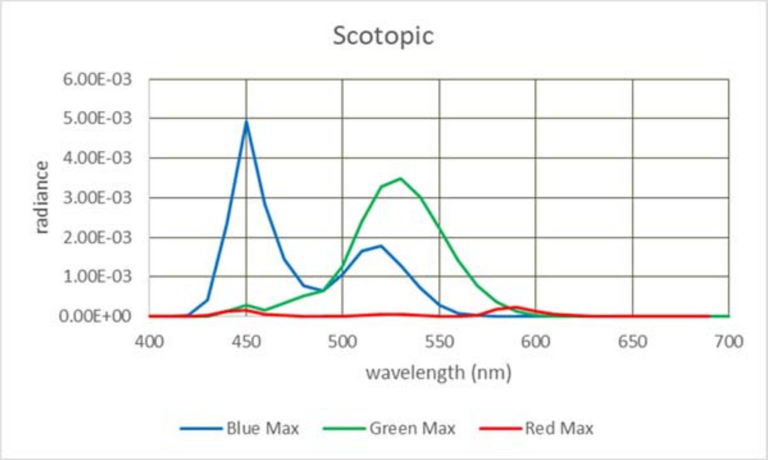


Figure 7. Scotopic plots of iPad for RGB curves that produce white target.

The color of objects has been determined by the International Commission on Illumination (CIE) in CIE (1932). *Commission internationale de l'Eclairage proceedings, 1931*. Cambridge: Cambridge University Press.

Using X, Y, and Z coordinates that represent the human eye relative sensitivity to short, medium, and long cone cells. These three values compose a tristimulus specification of the objective color of the light spectrum. Figure 8 shows the CIE X, Y, and Z tristimulus curves (solid lines) and the RGB curves of the iPad Mini 3 (dashed lines).

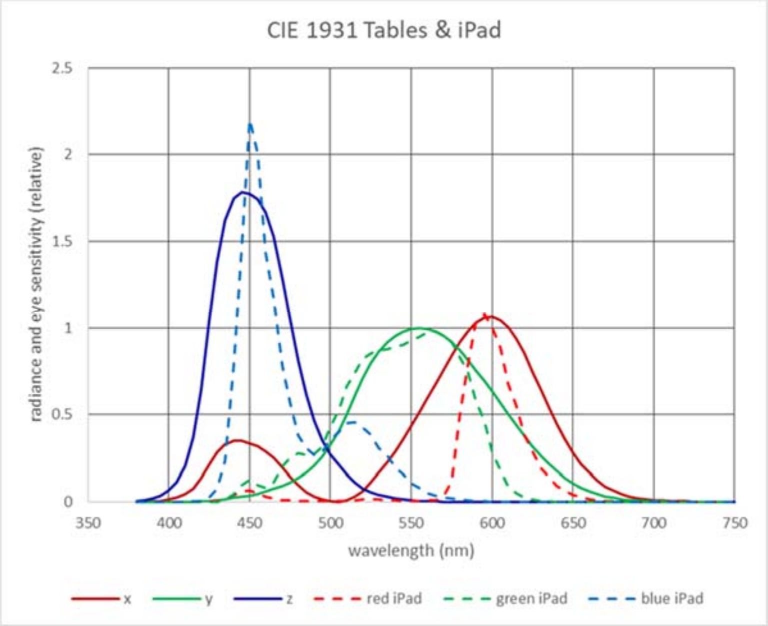


Figure 8. RGB iPad spectral curves and CIE X,Y,Z tristimulus curves.

Figure 9 shows the CIE 1976 Chromaticity Diagram in u’, v’ co-ordnance and the RGB targets using the iPad Mini 3.

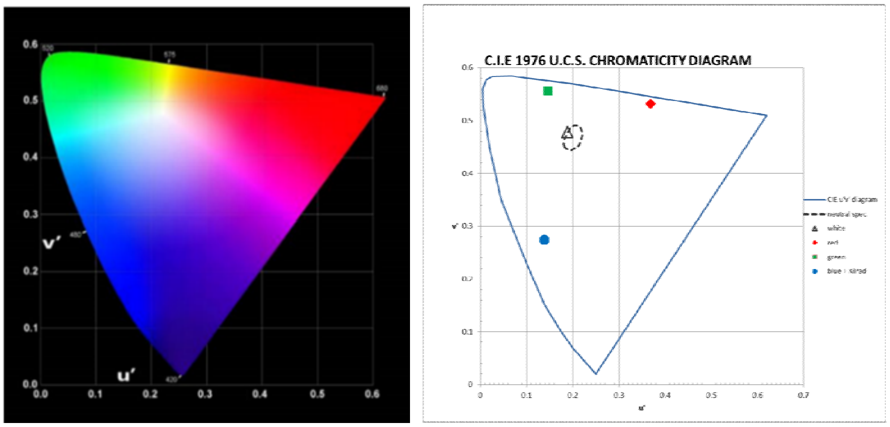


Figure 9. International Commission on Illumination Chromaticity Diagrams
CIE (1932). *Commission internationale de l'Eclairage proceedings, 1931*.
Cambridge: Cambridge University Press. CIE with the iPad RGB colored plots.

Table 1 lists the measured photopic and scotopic luminance of the iPad targets with the u’,v’ CIE color coordinates as well as the NVIS radiance with 12% visible transmission NVG compatible filter at lowest brightness setting used in the laboratory and field detection studies. Also included in the table are the ratios of the scotopic to photopic luminances. Table 2 lists the ratio of each color to white and the sum of the RGB colors equals the white target.

Table 1. Circular Target Luminance and Night Vision Imaging System Radiance on iPad Mini 3

Color	***Photopic* (fL)**	***Scotopic* (fL)**	**C.I.E Color**		***Scotopic* / *Photopic* Ratio**	**NVIS 3 Radiance [W cm-2 sr-1]**
			u’	**v’**		
White	0.335	0.748	0.1881	0.4763	2.235	1.92E-07
Red	0.0804	0.022	0.3418	0.5374	0.274	5.80E-08
Green	0.209	0.363	0.1465	0.5559	1.738	1.09E-07
Blue	0.0505	0.3561	0.1376	0.2742	7.045	2.36E-08
Black	3.93E-4	8.80E-4	0.1807	0.4246	2.240	3.58E-10 (cal)

Table 2. Ratio of Colored Target *Photopic* and *Scotopic* Luminance to White

Color to White Ratio	***Photopic* (fL)**		**Color to White Ratio**	***Scotopic* (fL)**
White	1.00		White	1.00
Blue	0.15		Blue	0.48
Green	0.62		Green	0.49
Red	0.24		Red	0.03
Black	0.001		Black	0.001
Red + Green + Blue	1.01		Red + Green + Blue	1.00

Figure 10 shows the NVG compatible filter spectral transmission used in the laboratory and field studies. Figure 11 shows the transmission of the white and red colors in log plots, with and without the NVG compatible filter.

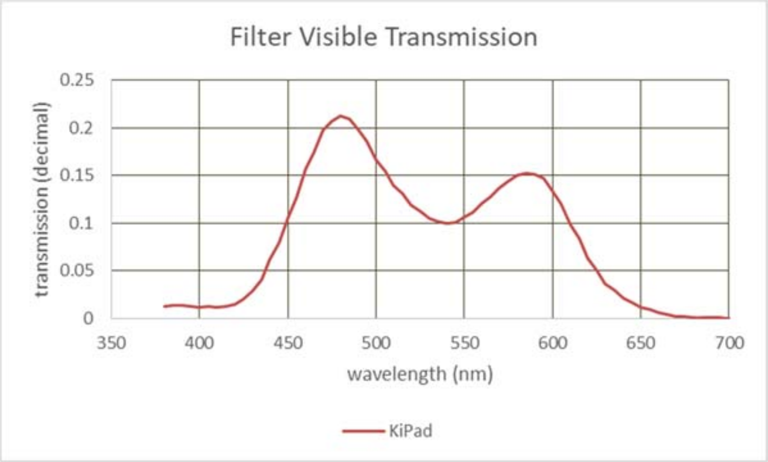


Figure 10. Night Vision Goggle compatible filter transmission (linear plot).

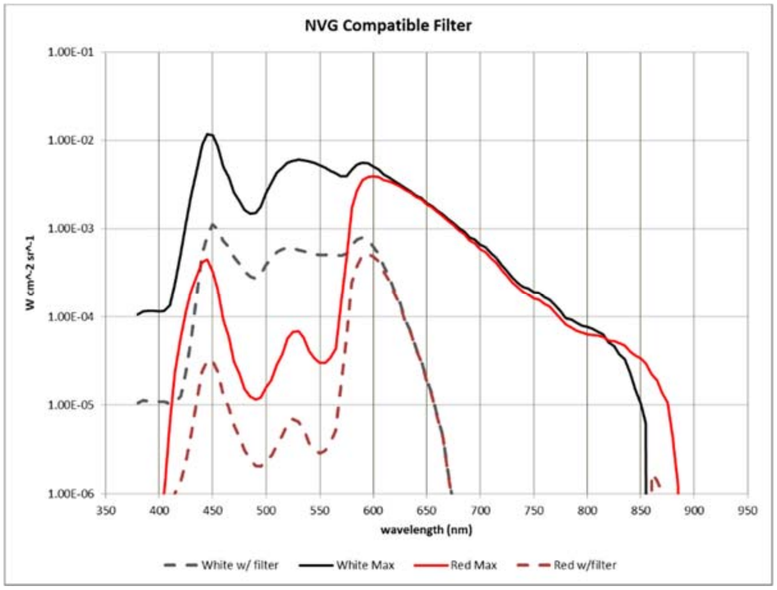


Figure 11. Night Vision Goggle compatible filter transmission (log plot).

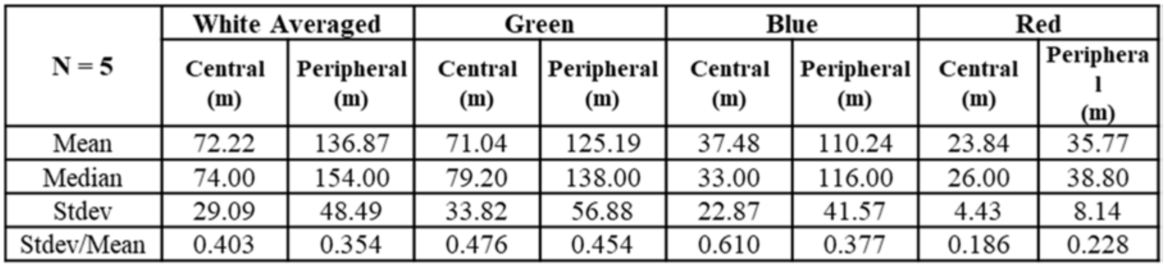
Visual detection ranges are primarily based on the target size (area) and the target/background luminance (photopic or scotopic). The targets on the iPad used in the USAARL storage room range were either 1 or 2 millimeters (mm) in diameter. One mm on the iPad equals 13 pixels. We discovered early that even though the black background luminance of the iPad with filter was approximately 0.1% of the white target and average only approximately 3.5E-4 fL, the background area on the iPad was over 6 thousand times the area of a 2 mm round target. This resulted in the dark adapted eye being able to see the “black” background without a target at greater ranges than the targets. For the indoor range, we used a black paper opaque mask with a central 6 mm aperture to cover 99.85% of the iPad background.

The average gain (input fL to output brightness fL) of the three AN/PVS-14s MNVD, measured with the Hoffman ANV-126A was 8,700 to 1.

Phase 2—Laboratory Detection Range (3 to 19 m)

Data listed in table 3 is reported as 8 mm targets, calculated from the 1 and 2 mm diameter targets used in the actual laboratory range. Data are shown from five subjects for the indoor range since one subject exceeded the peripheral detection range for white and green targets even with the 1 mm target and an additional 50% filter. Table 3 shows the calculated mean, median, and standard deviation (Stdev) distances from the laboratory data that 8 mm targets data would have been detected and for the 8 mm targets used in the field study for 5 subjects. Table 4 lists the field data for the 8 mm targets for the same five subjects used in the laboratory range study

Table 3. Detection Data, Laboratory Range, Calculated for 8-mm Target for Five Subjects

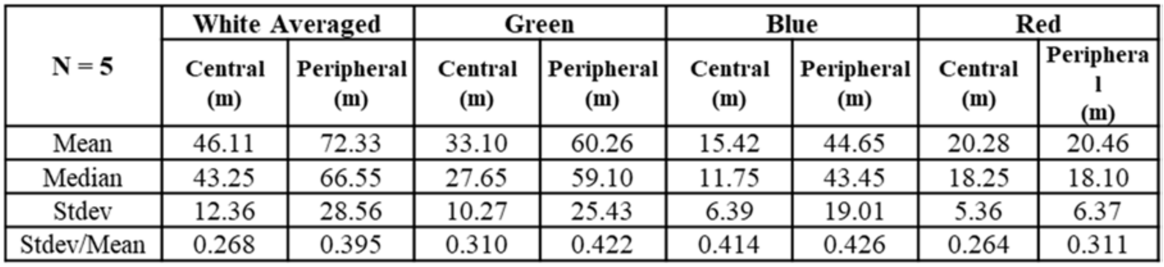


N = 5	White Averaged		Green		Blue		Red	
	Central (m)	Peripheral (m)	Central (m)	Peripheral (m)	Central (m)	Peripheral (m)	Central (m)	Peripheral (m)
Mean	72.22	136.87	71.04	125.19	37.48	110.24	23.84	35.77
Median	74.00	154.00	79.20	138.00	33.00	116.00	26.00	38.80
Stdev	29.09	48.49	33.82	56.88	22.87	41.57	4.43	8.14
Stdev/Mean	0.403	0.354	0.476	0.454	0.610	0.377	0.186	0.228

Phase 3—Field Detection Range (5 to 160 m)

Table 4 lists the field data for the 8 mm targets for the same five subjects used in the laboratory range study.

Table 4. Detection Data, Field Range, Measured for 8 mm Target for Five Subjects



N = 5	White Averaged		Green		Blue		Red	
	Central (m)	Peripheral (m)	Central (m)	Peripheral (m)	Central (m)	Peripheral (m)	Central (m)	Peripheral (m)
Mean	46.11	72.33	33.10	60.26	15.42	44.65	20.28	20.46
Median	43.25	66.55	27.65	59.10	11.75	43.45	18.25	18.10
Stdev	12.36	28.56	10.27	25.43	6.39	19.01	5.36	6.37
Stdev/Mean	0.268	0.395	0.310	0.422	0.414	0.426	0.264	0.311

Field data are also shown in Table 5 for the six subjects to include the one subject in the laboratory range that exceeded the peripheral range detection limits for white and green targets. Detection data for AN/PVS-14 monocular NVD (Table 6). Note detection data is for the red target with a NVG compatible filter using central vision.

Table 5. Field Data for Six Subjects

N = 6	**White Averaged**		**Green**		**Blue**		**Red**	
	Central (m)	**Peripheral (m)**	**Central (m)**	**Peripheral (m)**	**Central (m)**	**Peripheral (m)**	**Central (m)**	**Peripheral (m)**
Mean	45.16	77.40	33.57	64.92	14.52	47.21	19.88	20.43
Median	41.84	68.35	31.78	60.35	11.53	45	18.08	19.2
Stdev	11.30	28.41	9.26	25.44	6.13	18.12	4.89	5.70
Stdev/Mean	0.250	0.367	0.276	0.392	0.422	0.384	0.250	0.279

Table 6. Detection Data for the AN/PVS-14 Monocular Night Vision Device

N = 6	**Red (m)**
Mean	107.41
Median	98.98
Standard deviation	35.72
Stdev/Mean	0.333

As expected, the laboratory data consistently show greater visual detection ranges than the field data when calculated for 8 mm diameter targets since the laboratory data were taken in absolute darkness, and the field data were acquired during starlight ambient illumination. Also the mask used to block the black background on the iPad was 6 mm in diameter for the 1 and 2 mm targets used. In the field, 8 mm masks were used which completely blocked out the iPad background without any possible additional luminance.

Figure 12 shows the field detection range data calculated for equal photopic luminance matched to the white target. Note that the detection ranges for central (foveal) vision are approximately the same except for the blue target where photopic luminance underestimates the detection range. The peripheral detection ranges with photopic luminance values show increased ranges with the shorter wavelengths (blue).

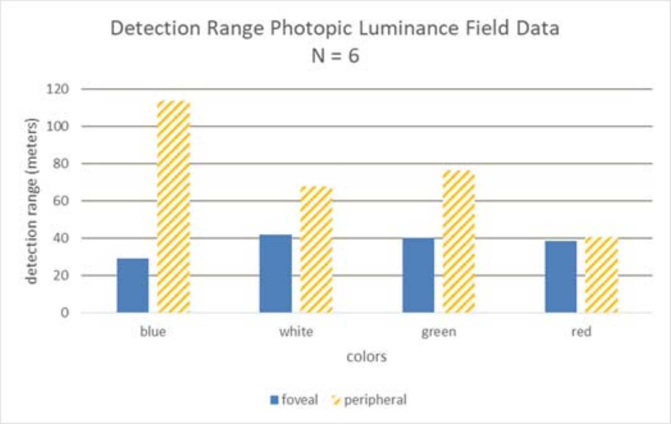


Figure 12. Central and peripheral field detection ranges for targets matched for white *photopic* luminance.

Figure 13 shows the detection range data calculated for equal scotopic luminance matched to the white target. Note the estimated detection ranges when the luminance is matched while *scotopic* luminance show very little agreement with central or peripheral fixation.

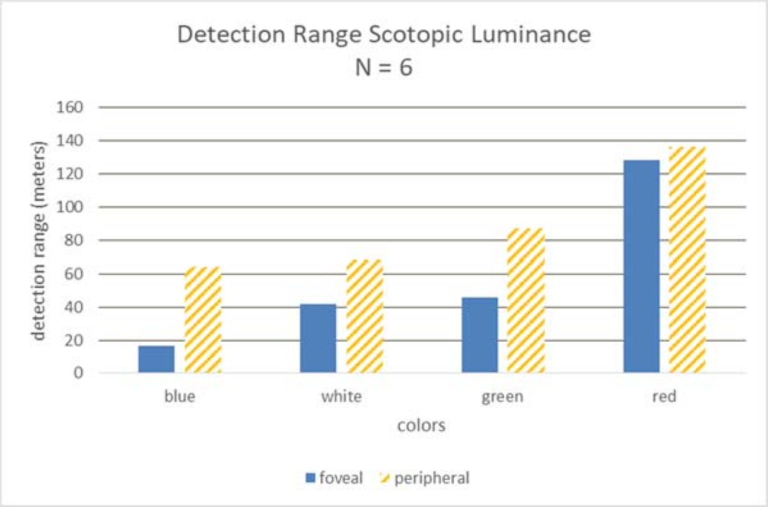


Figure 13. Central and peripheral field detection ranges for targets matched for white scotopic luminance.

Figure14 shows the calculated ratios of the median peripheral detection ranges for the RGB and white targets. Note peripheral fixed and central fixated distances are almost the same for the long wavelength red, and almost four times greater for short wavelength blue. There are very few blue cones in the foveal area, and very few red cones in the peripheral retina.

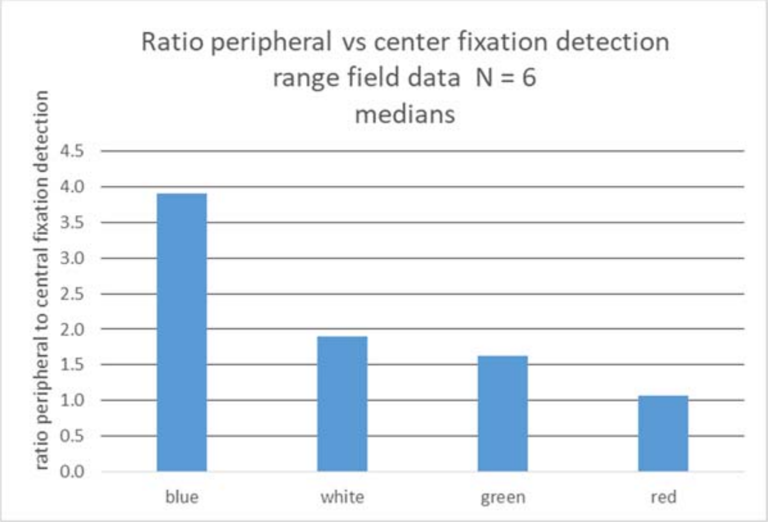


Figure 14. Ratio of peripheral to foveal field detection ranges for colored targets.

Since neither the photopic or scotopic target luminance values correlated well with the peripheral detection ranges for the starlight field conditions, we explored empirical analysis to predict the peripheral detection ranges from the photopic measurements and the calculated scotopic/photopic ratios. Figure 15 shows the regression analysis and resultant equation to calculate the peripheral detection factor or ratio between central and peripheral fixation. The equation is: y = 0.4153x + 0.956, where y is the peripheral/central detection range ratio, and x is the scotopic/photopic ratio. With only four data points, the confidence in the peripheral range ratio is uncertain for middle visual wavelengths, but that is another study. Note in the previous Table 1 that the scotopic/photopic ratio for blue is approximately 7, and for red 0.3. The white scotopic/photopic ratio is approximately 2.2, and green 1.7.

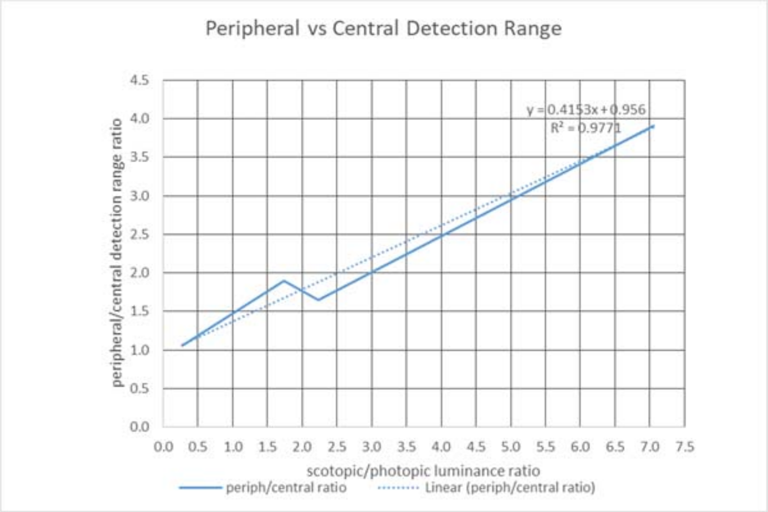


Figure 15. Peripheral/central field detection range versus the *scotopic* to *photopic* luminance ratio.

Figure 16 shows the detection ranges for central and peripheral vision from the calculated field data, and the comparison of the peripheral model based on just the central photopic detection data and regression factor derived from the scotopic to photopic ratio.

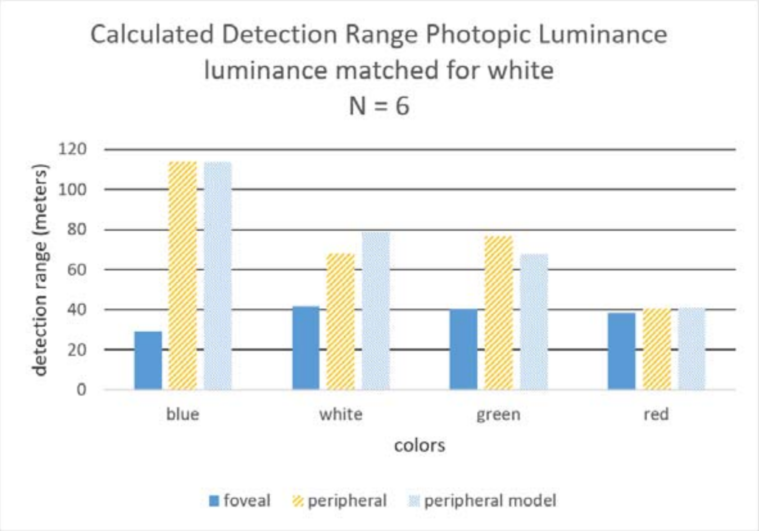


Figure 16. Detection ranges for central and peripheral fixation with calculated peripheral field detection range model.

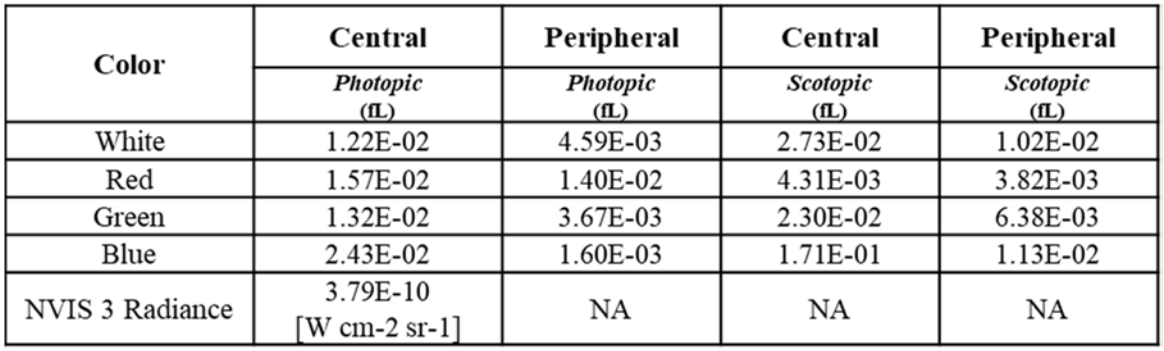
Conversion of luminance

Calculation of 100 mm diameterTarget Luminance and NVIS radiance to detect at 100 m. Circular target luminance (fL) and NVIS radiance on iPad..

1. Convert 8 mm target luminance to 100 mm diameter target luminance by multiplying 8 mm luminance target luminance (fL) x (8/100)^2 factor or 0.0064.
2. Calculate target intensity to detection at 100 m by (100/actual detection distance)^2 time (x) target intensity (fL).
3. Calculate target intensity to detection at 1 km by multiplying #2 value for 100 m time (x) 10^2 or 100.

For the field data, Table 7 gives the calculated target luminances of the colored targets and radiance of 100 mm discs that could be detected at 100 m, based on the median data of 6 subjects.

Table 7. Luminance and Night Vision Imaging System Radiance of 100 mm Diameter Disc Detectable at 100 m Under Starlight Illumination



Color	**Central**	**Peripheral**	**Central**	**Peripheral**
	Photopic **(fL)**	***Photopic*** **(fL)**	***Scotopic*** **(fL)**	***Scotopic*** **(fL)**
White	1.22E-02	4.59E-03	2.73E-02	1.02E-02
Red	1.57E-02	1.40E-02	4.31E-03	3.82E-03
Green	1.32E-02	3.67E-03	2.30E-02	6.38E-03
Blue	2.43E-02	1.60E-03	1.71E-01	1.13E-02
NVIS 3 Radiance	3.79E-10 [W cm-2 sr-1]	NA	NA	NA

Discussion

Target luminance, NVIS measuring methods and comparison to MIL-STD-3009, *Lighting, Aircraft, Night Vision Imaging System (NVIS) Compatible.*

The intensity of a light source as seen by the human eye is measured with a photometer. Various units of measurement are used, but the most frequent ones are foot-lamberts (fL) and nits (candelas/m2) (U.S. Department of Defense, 2001).

For image intensifier devices, the target luminance is a function of gain or the ratio of input brightness versus output brightness for input spectrum of Illuminate A and color temperature of 2856 degrees Kelvin. However, the human eye spectral sensitivity and the image intensifier tube spectral sensitivity are very different, so the gain factor for light sources other than an incandescent with 2856K color temperature will show different gains. Since the first introduction of the generation III image intensifiers in the early 1980s, the gain factor has increased 10 fold.

For image intensifiers, IAW MIL-STD-3009 the near infrared emitting from a light or reflected source is measured and calculated in units of Night Radiance (NR) (NRa, NRb, NRc) after the source has been scanned with a spectra radiometer in Watts/cm2 sr nm (Calculatorology;, N.D.).

Unfortunately, we are not aware of a NR total flux unit. The NRa, NRb, NRc refer to the minus blue filters in the objective lenses of the Aviator's Night Vision Imaging Systems (ANVIS). These filters are used in the ANVIS objective lenses to block the visible wavelengths of the aircraft cockpit lighting and displays to reduce the light interference to the pilots for outside viewing. Figure 17 shows the normalized spectral sensitivity of the Generation III image intensifiers, and the transmissions of the Class A, B, and C minus blue filters (Calculatorology, N.D.).

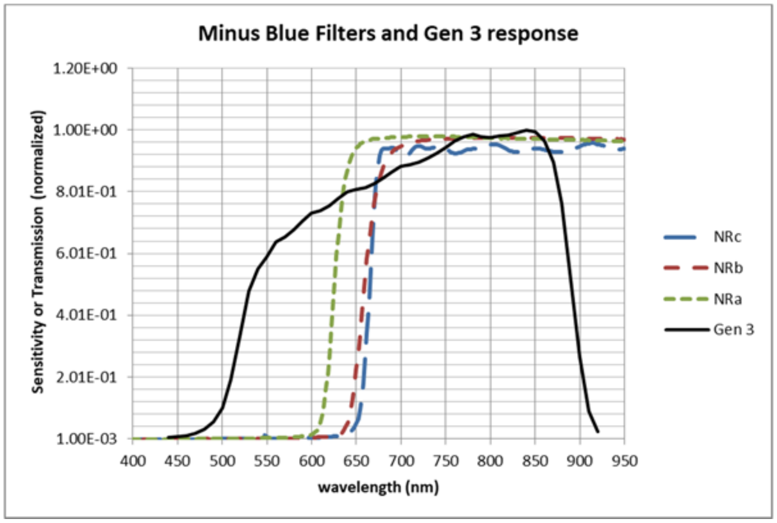


Figure 17. Generation III spectral sensitivity and Class A, B, and C filter transmission.

However, the non-filtered NVGs used by ground soldiers and possible adversaries will amplify all visible wavelengths and increase the NVG signatures when viewed from outside the aircraft. In calculating the detection ranges with NVGs, we use the unfiltered NVIS radiance computed for a 100 mm diameter target, and computed from our median detection range from our field iPad data.

For target detection under low light conditions with the unaided eye or with night imaging systems, it is a combination of both luminance-NR and target size in area units. The target intensity times (x) the target area is a constant under starlight ambient illumination. For evaluating visual and image intensifier signatures for aircraft and carry on equipment lighting, the area and intensity of the emitting light source must be determined or at least estimated. MIL-STD-3009 does not include radiance units or methods to address signatures with different target or display sizes. This will be further discuss in the calculation section.

Photopic, *Scotopic*, and/or Mesopic, Observers' Dark Adaptation and Variability

If we are determining the ranges for detection of light sources at night, we would assume the units of light measurement would be *scotopic* units. In this study, we included both foveal fixation and peripheral fixation to determine the detection ranges. However, the detection ranges with central/foveal vision was more related to *photopic* luminance values (previous Figures 12 and 13). Foveal vision is predominately cone vision (*photopic*); whereas the rods dominate with peripheral vision (*scotopic*) (Figure 18) (Kalloniatis & Luu, 1995).

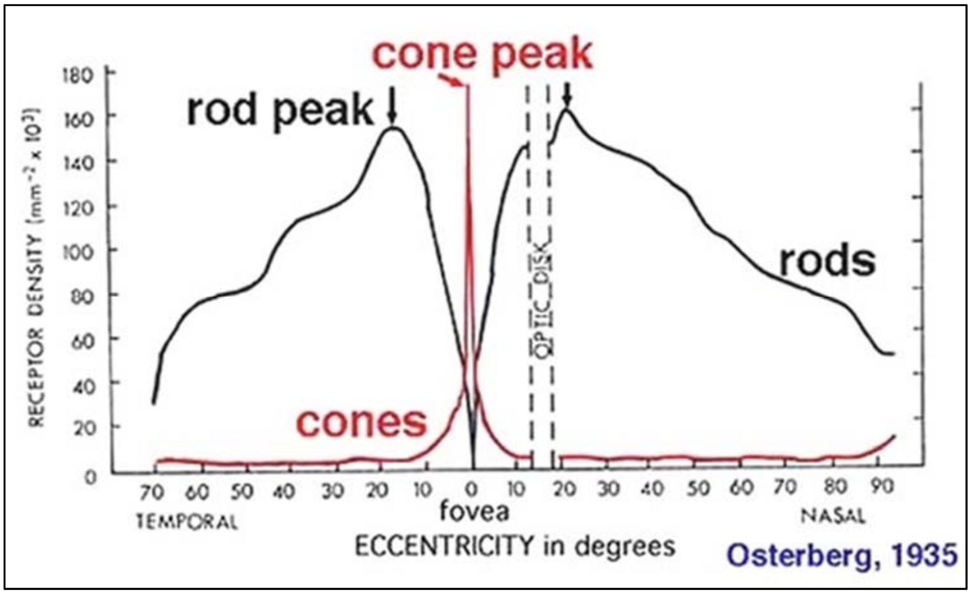


Figure 18. Cone and rod density measured in degrees from fovea from Gustuv Osterberg's *Topography of the layer of rods and cones in the human retina* (1935).

The central vision detection under starlight ambient illumination correlated well with the photopic target luminance measurements, with the exception of the blue target. The peripheral detection distances were more related to the scotopic measurement values, but the correlation was not as good as with photopic and central fixation. Using a regression model of the scotopic/photopic ratio and the field detection data, the peripheral detection ranges could be computed from just the photopic central fixating data. As the eyes dark-adapt, the central or foveal vision decreases in sensitivity compared to the peripheral vision (Figure 19) for a white light with changing background luminance. Background luminance at starlight was approximately 5E-05 fL (Kalloniatis & Luu, 1995).

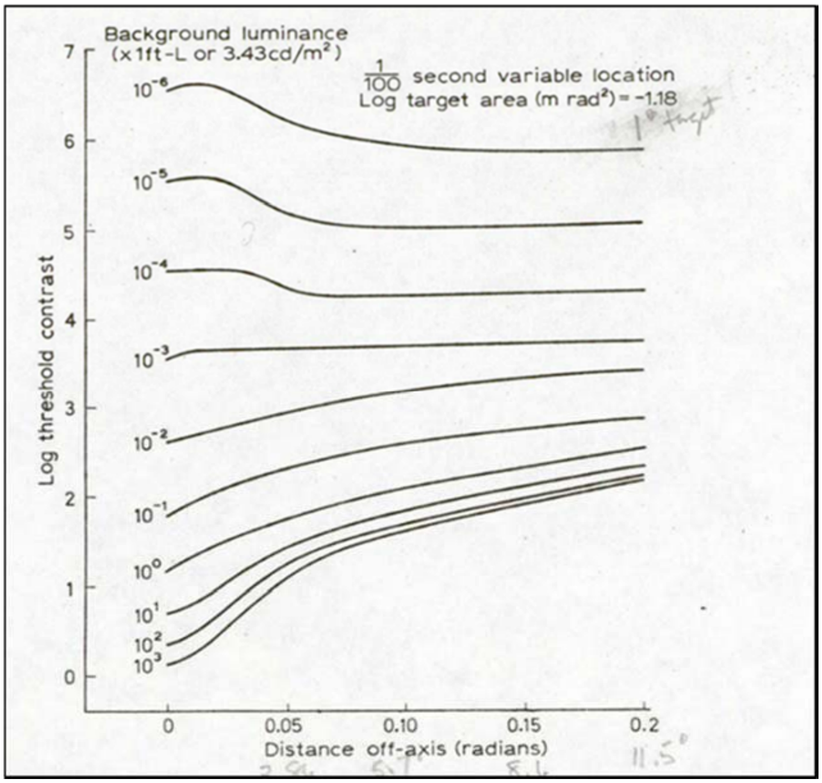


Figure 19. Foveal and peripheral retinal sensitivity with dark adaptation. Ovington (1976)

As the target spectrum shifts from the red long wavelengths to the shorter blue, violet spectrum, the eye increases in sensitivity with increasing dark adaptation (Overington, 1976).

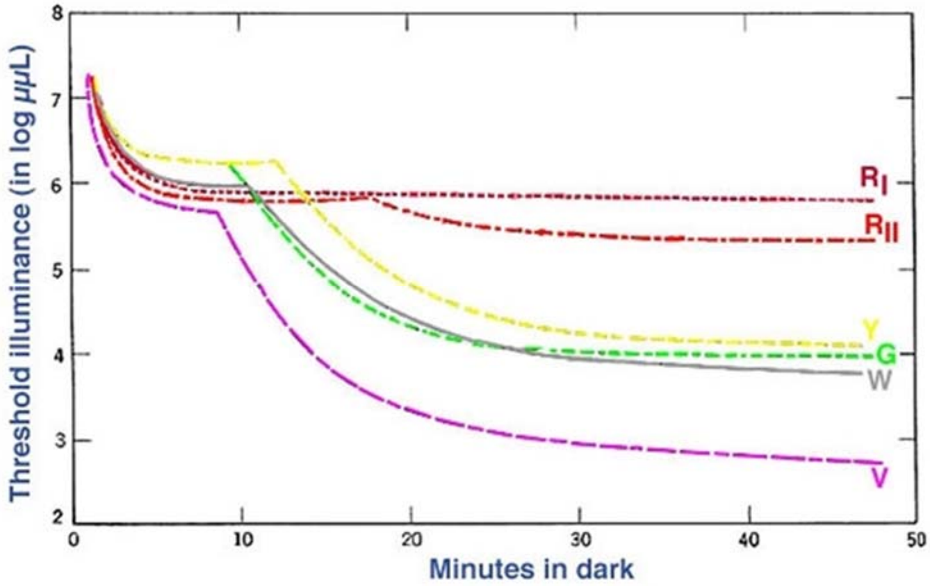


Figure 20. Dark adaptation curve using different test stimuli of different wavelengths. Chapanis' data are from Bartlett (1965).

Subjects were pre-adapted to 2,000 mL for 5 minutes. A 3° test stimulus was presented 7° on the nasal retina. The colors were: RI (extreme red), 680 nm; RII (red), 635 nm; Y (yellow), 573 nm; G (green), 520 nm; V (violet), 485 nm; W (white).

Figure 21 shows the variability of dark adaption for a given population. Note there is approximately a 1 log unit difference for a given time period after 10 minutes. The gray area represents 80% of the group of subjects (Kalloniatis & Luu, 1995).

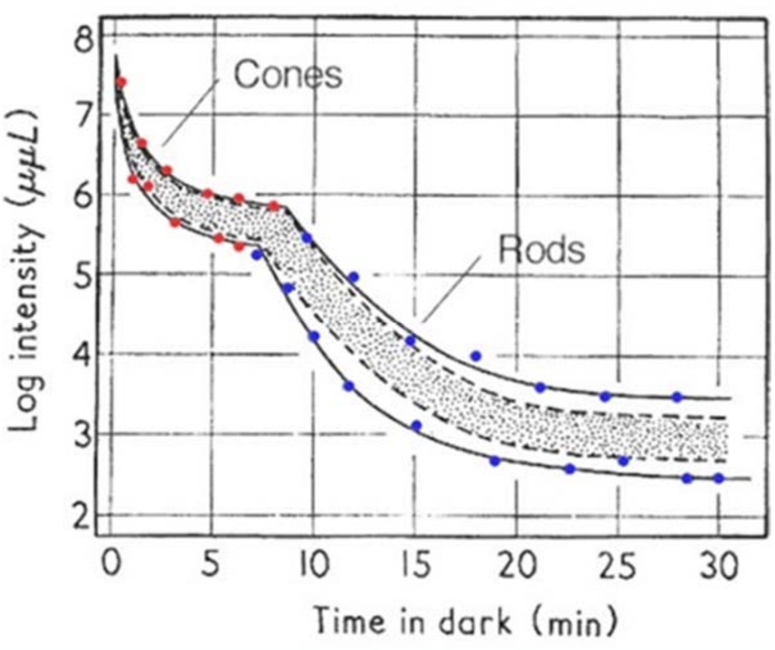


Figure 21. Dark adaptation versus time and population variability. Fisher, Kenneth D ; Carr, C Jelleff (1970), and Kalloniatis, M., & Luu, C. (1995).

At the starlight level, the eye adaption is close to the maximum possible. Therefore, the range to detect the target lights would not significantly increase any further with reduction in ambient illumination. Figure 22 shows this effect (Kalloniatis & Luu, 1995).

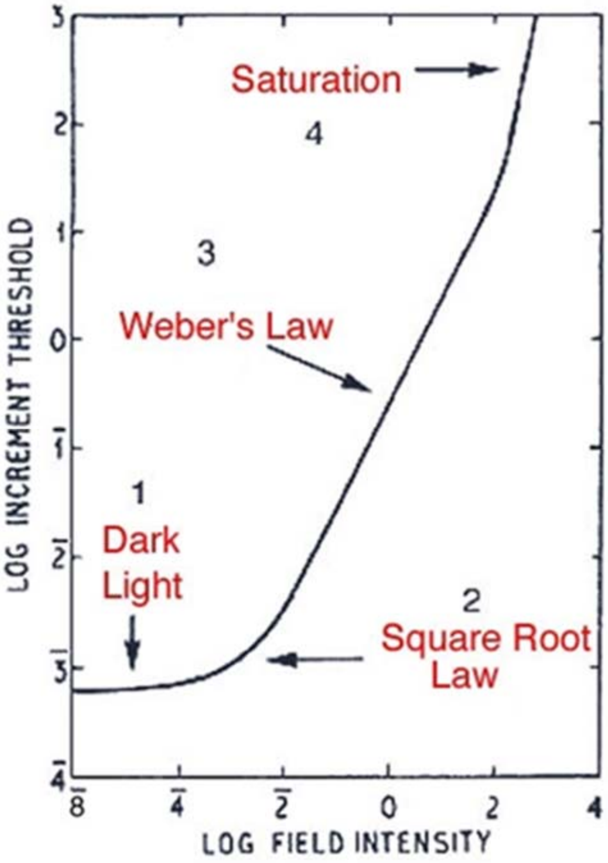


Figure 22. Effect of ambient (field) background and target contrast. Kalloniatis, M., & Luu, C. (1995). https://www.ncbi.nlm.nih.gov/books/NBK11525/

The threshold in the near horizontal segment of the three component curve (Figure 22) is the intensity of the light which does not increase with darker light levels. Sensitivity in this section is limited by neural (internal) noise, the so-called "dark light". The detection range in this segment follows the square root law of target intensity versus detection range. Above a certain light level, the detection range is based on weber contrast (Lt-Lb)/Lb, where Lt is the target luminance and Lb. is the background luminance.

Which is more important, direct viewing or peripheral detection?

As the data have shown, the peripheral detection ranges were greater than the direct view ranges for the totally dark laboratory and starlight field studies. The target color or scotopic/photopic ratio determined the increase peripheral detection ranges. The single glimpse probability of detection is based on the area of the retina the target can be seen versus the area of visual search, assuming the target and eye fixations could be located randomly within the search area. In the case of a red target at maximum detection range at starlight, the target could be seen centrally within a few degrees from the fovea, but not in the periphery. For the blue target, the maximum detection range was over three times greater with peripheral viewing than direct viewing in the fovea. The area on the retina for detection would be greater for blue and higher probability of detection. However, when attempting to view the blue directly, the target could disappear, which would make aligning a weapon sight and target identification more difficult. It would appear that both direct viewing and peripheral detection are important for tactical observations. Training, experience, and retaining dark adaption will improve the observer's performance.

Control of target and background lighting conditions

Before the iPad Mini 3 Before the iPad was selected as a target stimulus, measurements of the output luminance for white, red, green, and blue circles were taken with the brightness settings adjusted to maximum, and the minimum values. The measurements were taken using the Pritchard 1980A and the 1-degree Minolta photometer with the iPad battery levels from 100% to less than 30%. The measurements were within measurement error of approximately 5%.

In the laboratory range, the background light level was below the sensitivity of the Pritchard photometer. Also through the AN/PVS-14, optically coupled to the Minolta photometer, the eyepiece luminance was less than 0.01 fL.

In the field, all test data were taken under starlight conditions with no moon illumination at least 1 hour after sunset. However, the background and sky luminances varied somewhat from sky conditions with occasionally scattered clouds reflecting ambient illumination from cultural lighting for some subjects. Measuring through the AN/PVS-14, the lowest readings were 0.08 fL for the ground and 0.48 fL for the sky, and the highest measurements were 0.4 ground and 1.6 fL for the sky during the testing periods. For reference, during four medical carry on equipment NVG assessments under starlight conditions at a Fort Rucker remote helicopter stage field, the luminance on the white background of the tri-bar resolution chart through the AN/PVS-14 varied between 0.35 fL to 0.50 fL with clear skies. With the measured gain through the AN/PVS-14 of 8,700 to one for starlight, the calculated background illuminations on the chart would be 4.02E-05 and 5.75E-05, respectively. Sample size and comparisons of test results for indoor and outside range

Sample size and comparisons of test results for indoor and outside range.

This study was only designed to be exploratory to investigate the major variables and measuring methods for visual detection of circular targets of known size, color, and luminance. As expected under zero lighting levels in the laboratory, the calculated detection ranges for the same size target and intensity were greater than under starlight levels in the field. Table 8 shows the ratio of detection distances in the laboratory calculated for 8 mm targets with the 8 mm targets in the field. Although the field ambient luminance levels were more variable than the laboratory range, the field data will be of greater value for estimating worse case detection ranges of medical equipment at star light directly viewed.

Table 8. Ratios or Detection Factors of Total Dark Laboratory vs Field Data Equalized for 8 mm Targets

N = 5	White Averaged		Green		Blue		Red	
	Central (m)	Peripheral (m)	Central (m)	Peripheral (m)	Central (m)	Peripheral (m)	Central (m)	Peripheral (m)
Mean	1.57	1.89	2.15	2.08	2.43	2.47	1.18	1.75
Median	1.71	2.31	2.86	2.34	2.81	2.67	1.42	2.14

Note the larger detection distance ratios of lab to field data with blue and smaller ratios for the red, with green and white in between.

The initial approved test plan requested the participants to report when they were 95 and 50% sure they could detect the targets. After the first three participants in the laboratory range, the test plan reviewers and participants agreed the better instructions would be to report when they could see it when moving towards the targets, and when they could not see it when moving away from the targets. With either instruction, the differences between seen, 95%, 50%, and not seen were only a few paces. All of the field trails used the "see, or not see" criteria

Night Vision Goggle detection issues (monocular/binocular)

Target detection estimates with NVGs include numerous variables. To list a few major ones: ambient illumination, background near infrared reflectance, as well as the type and performance of the NVG. For medical equipment in the rear of the aircraft, the lower the ambient illumination, the higher probability of the equipment lighting being a major visual signature. The location of the medical equipment in the aircraft will varying from worse case with direct viewing to reflections in the interior and windscreens. NVG type and year produced have performances parameters such as gain varying by a factor of 10 or more. Fielded ground use NVGs are both monocular and binocular. A binocular NVG with the same image intensifier tubes as a monocular NVG will have an improvement in viewer resolution and gain of 1.41 or square root of 2.

Suggested follow-up research and approaches

To obtain an AWR for medical carry-on equipment in aircraft, the NVG compatibility and signature issues will continue with field assessments under starlight conditions for each proposed medical device. From our previous NVG assessments, the procedures to determine effects on ANVIS acuity outside the aircraft showed no effects for equipment located in the rear. However, unaided and aided visual signatures of the equipment inside the aircraft within engagement ranges were the usual finding. The iPad with larger circular targets could be used to explore detection ranges within the cabin of the aircraft from reflections of the interior and into the windscreens in different locations. The circular targets on the iPad can be adjusted in size and intensity and measured with a hand held photometer.

Conclusion

As an exploratory study to investigate and attempt to quantify the night signature issues of medical carry on equipment, the following information was learned:

1. Most likely, the greatest detection ranges would be under starlight.
2. There is much more variability in *scotopic* detection ranges among observers than best acuity values.
3. Color and/or the *scotopic/photopic* ratio is a major factor in central versus peripheral vision detection where the shorter visual spectrum targets have more peripheral vision sensitivity.
4. The previous methods of measuring light sources in candela units for viewing in *scotopic* and *mesopic* light levels do not consider the Purkinje shift where the eye becomes more sensitive to the shorter wavelengths such as blue. The field detection study analysis describes a method to estimate both central and peripheral viewing detection under starlight illumination from the *photopic* light measurements and the *scotopic/photopic* ratio.
5. The laboratory measuring method, calculating a target size and luminance with spectral scans, allows the effects of multiple light sources to be additive for computing detection ranges.
6. Using the iPad or similar portable displays as a target generator can produce repeatable luminance and chromaticity values for laboratory and field studies.

- Methods to mitigate target luminance and signature for medical carry on equipment in the visual and near IR spectrum should be explored. In addition to filters and location within the aircraft, simple, readily available materials to cover the equipment when on the ground or during take-off and landings might be just as effective as expensive NVG compatible filters.

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Acronyms and Abbreviations

ANVIS	aviation night vision system
AWR	Airworthiness Release
cm	Centimeters
fL	foot-lamberts
CIE	International Commission on Illumination
IR	infrared
Lb	background luminance
lm	lumens
Lt	target luminance
m	meters
mm	millimeters
MNVD	monocular night vision device
NA	not applicable
NR	night radiance
NVIS	night vision imaging systems
NVG	Night Vision Google
PI	principal investigator
RGB	red, green, and blue
sr	steradian (symbol: sr) or square radian
W	watts
USAARL	U.S. Army Aeromedical Research Laboratory

Appendix A. Briefing to Subjects

To participate in this study, you must be a volunteer and have permission from your supervisor to participate in this study for the time required for briefing, practice, and data collection. In order to take part in this research study, you should have 20/20 vision in each eye, with or without corrective lenses, be less than 36 years of age and less than 6’ 2” tall to avoid overhanging pipes in the laboratory study in the USAARL basement. If you do not meet these criteria, thank you for your time and hopefully you can participate in future USAARL studies.

Purpose

The purpose of this exploratory study is to determine estimated detection distances of small well defined light sources with different colors and intensity under starlight or darker light conditions. The colored circular targets will be presented on an iPad Mini 3. This study will be conducted in the laboratory with targets selected for detection distances less than 20 meters. At a later date a field study will be conducted at night under starlight illumination with larger targets and detection distances out to 100 meters. The field study will be with the dark adapted unaided vision, and using a single tube AN/PVS-14 Night Vision Goggle (NVG). The laboratory study should take less than 2 hours for the briefing, practice, and data collection. The field study could take up to 3 hours.

Procedure

The laboratory assessments will be conducted in the USAARL storage room T-4. Prior to the practice trials, you will be briefed on the optimum methods for detection when dark adapted using off center and foveal vision and the differences in detection for the different colored target circles.

You will dark adapt for 5 minutes, and start the practice trials even though not fully dark adapted at this time. You will begin viewing the iPad Mini 3 with a small circular target of a given size (1 or 2mm diameter) and color (red, green, blue, white) at a range where the circular target cannot be detected. A blinking small dim red LED will be located about 1 meter (3 ft) to the left of the iPad Mini 3 for orientation and guide for central and peripheral viewing. You will step towards the iPad Mini 3 in one step increments (1/2 meter), stopping for about 8-10 seconds and responding with each step if you think you can see the target circle and tell the color using direct foveal fixation and slightly off axis fixation. Each detection distance will be recorded by a research team member using a red flashlight and not within your view. When you are sure you can see the target looking directly at it, you will begin stepping backwards until you report you can’t or not sure you can see the target. This will be the first data point. We will begin the next trial using the staircase method by stepping forward in one step increments to identify when you can see it again. The distances to detect the target with peripheral vision will follow before the target color is changed. The practice trial will consist of one target size and all four colors. Each color and target size will have 3 trials of 6 data points for each participant starting and finishing with the color white. After three trials for a specific color, you will begin at the maximum viewing distance (18 meters) for the next color trial.

The field assessments will be conducted on 33rd street below the Veterinarian Clinic in the Tank Hill area after sunset. Prior to the practice trials, you will be briefed on the optimum methods for detection when dark-adapted using off center and foveal vision and the differences in detection for the different colored target circles. The target sizes on the iPad Mini 3 will be larger than the laboratory trials. The ranges will be marked off in 10 meters with small orange tags. Using the same procedures as in the lab, you will start at a viewing distance you are sure you can detect the target and tell the color. You will then take steps backwards until you are not sure you can see the target. This will be the first data point. You will then step forward until the target is detected first using direct view vision. The procedure will be repeated using peripheral vision before the target color is changed.

Appendix B. Method of Measuring Target Luminance and Conversions to Candle Power

To determine if the iPad Mini 3 and medical carry-on equipment luminance, the C.I.E. color co-ordinance, and Night Vision Imaging System (NVIS) radiance, a Photo Research PR 735 spectral-radiometer was used. The largest entrance aperture cone is 2 degrees.

The primary instrument used for measuring luminance and candlepower is the Photo Research Pritchard 1980A photometer. The Pritchard photometer has selectable entrance apertures between 2 arc minutes to 3 degrees. To obtain an accurate reading of luminance in candelas per meter squared (cd/m^2) or foot-lamberts (fL), the aperture cones must be within the area of the target. The target has to be larger than the circular aperture that integrates the luminance flux within the size aperture selected. Smaller apertures are proportionally less sensitive than the larger apertures. If the target is smaller than the instrument measuring aperture, the luminance reading would be proportional to the relative size of the target area to the size of the measuring aperture (cone) for a given measuring distance. NOTE: The actual instrument apertures (cones) are smaller than the labelled values on the instruments.

For measuring candlepower or candelas with the Pritchard 1980A, a calibration baffle IB-80E is attached to the standard 50 mm lens of the photometer to compensate for actual aperture size. The baffle is 29 mm in diameter, and reduces the input luminance values by a factor of 0.57X. The instructions in the operator's manual follow:

1. Select the 3 degree aperture and place object within the aperture (object is smaller than aperture).

2. Divide the reading by 1000, which is in units of foot-candles (lumens per square foot).when instrument is set for fL or lumens per meter squared in SI units.

3. Compute the Luminous Intensity of the source using the following formula:

$CP = E \times d^2$

Where:

CP =candle power or candelas

E = Illuminance in foot-candles or Lux ($lumens/meter^2$)

d = distance in feet between the source or meters if SI units and measuring plane.

When using the PR 735 spectral radiometer with a 2-degree aperture and the target within the aperture, the following procedures and calculations were used to determine the equivalent luminance for candelas.

1. Convert measured luminance with PR 735 to 2 degree equivalent aperture by dividing value by (3/2)^2 or 2.25

2. Multiply this value by 0.57 for baffle factor used in Pritchard 1980A

3. Divide by 1000.

4. The candle power (candelas) is the calculated number in #3 above, multiplied by measuring distance in feet or meters squared if measured units are in fL or cd/m^{2,}, respectively.

Medical carry-on equipment can be very complex to quantify luminance, NVIS radiance, and size when they have displays and/or various lights of different colors, etc. For calculations of these complex targets, we can assign a target size since target luminance x target area is a constant for target sizes subtending less than a few digress. Using the PR 735, do the following:

1. Place target at a distance such that the labelled 2-degree cone aperture of the PR 735 completely covers the target.

2. Convert 2-degree aperture to radians (2*Π/180) = 0.0349 times actual aperture correction factor (0.57^0.5) = 0.0262. Note actual labelled 2 degree aperture is 1.5 degrees.

3. Select target size. We will choose a 100 mm (0.10 meter) disc.

4. Calculate the distance of 100 mm disc in actual instrument aperture. =0.10 meter/0.0262 = 3.817 meters.

5. Compute target luminance and NVIS radiance factor by the square of the ratio of actual distance measured, divided by the square of the distance to achieve actual aperture degree disc. For example, measured distance to target = 10 meters, 0.1 meter disc diameter for 1.5 degrees = 3.817 meters distance; computed target luminance = (10/3.817)^2 = 6.86 correction factor. The measured target luminance within the 1.5-degree cone times correction factor of 6.86 gives the target luminance of an equivalent target of 0.1-meter diameter or 100 mm.

6. To convert the target luminance (fL) of the equivalent target of 0.1-meter diameter (100 mm) to candelas, multiply by 0.0392.

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