This paper was cleared by ASC97-2079 on 14 Aug 1997

The Effects of Aircraft Transparencies on Night Vision Goggle-Mediated Visual Acuity

Alan Pinkus, PhD and H. Lee Task, PhD
Armstrong Laboratory
Crew Systems Directorate
Human Engineering Division
Wright-Patterson AFB, OH

ABSTRACT

Night vision goggles (NVGs) are currently used in a wide variety of military aircraft that were not originally designed for NVGs. Likewise, the windscreens and canopies on these aircraft were not designed with NVGs in mind. Present day windscreens and canopies typically have one or more specialized coatings applied to them. These may be reasonably transparent for visible wavelengths but not so transparent for near infrared light to which the NVGs are sensitive. It was hypothesized that the major mechanism by which aircraft transparencies affect the operation of NVGs is through reduced light levels. This would mean that the key characteristic of interest for determining the effect of an aircraft transparency on the operation of the NVGs would be its transmission coefficient calculated using the spectral sensitivity of the NVGs. This hypothesis was tested by investigating visual acuity performance of trained observers viewing through NVGs for three levels of ambient illumination (1, 2 and 5 times starlight) and three levels of NVG-weighted windscreen transmissivities (58, 76 and 100%). In addition, two levels of contrast were included in the study (20 and 70% modulation contrast). Three trained observers determined the orientation of a Landolt C using a two-alternative, forced-choice step paradigm. A luminance-based model was developed to smoothly combine the effects of illumination level and transmission level for each contrast thus supporting the hypothesis. In addition, the results demonstrate the significant difference between individual observer's performance level and the increased difficulty (higher variability) of performance at lower contrast levels.

INTRODUCTION AND BACKGROUND

Night vision goggles provide observers with the ability to see very dimly illuminated nighttime scenes by amplifying ambient light from the red and near infrared spectral energy region (600 through 950 nm; see Fig. 1). Anything that reduces the light level getting to the NVGs will tend to reduce the output luminance while at the same time decreasing the signal-to-noise ratio. This, in turn, tends to reduce the visual acuity of observers using the NVGs. These effects are most apparent at very low ambient light levels such as starlight illumination conditions. The basic hypothesis of this study is that it should not matter whether the light level is reduced by lowering the illumination level on the target area or by attenuating the light level getting to the NVGs by viewing through a transparency. This leads to the concept of equivalent illumination. For purposes of this study, equivalent illumination is the product of the actual illumination level and the transmission coefficient of the transparency through which one is viewing. As a specific example, the equivalent illumination for 2 times starlight actual illumination viewing through a 50% transmitting windscreen would be 1.0 starlight (2 times 0.5). This is the same equivalent illumination obtained for an actual illumination of 1 times starlight viewing through the NVGs with no intervening transparency (1 times 1.0). If the hypothesis is correct one would expect the visual acuity for these two conditions to be essentially the same (within the variability expected for human observations).

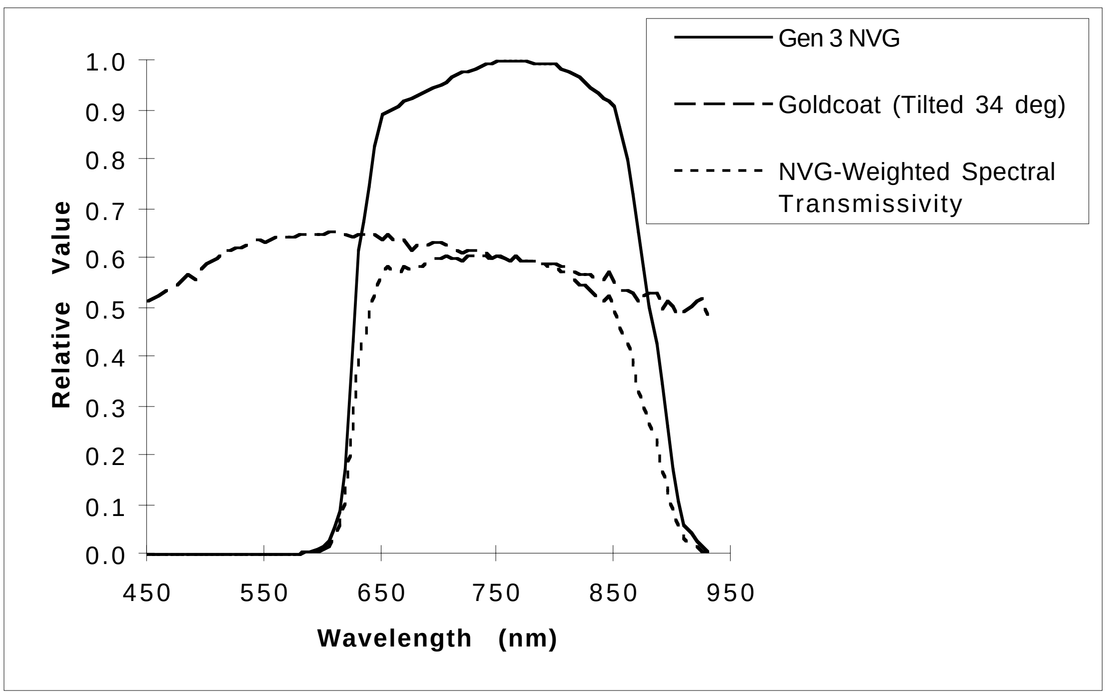

Figure 1. The relative value of a third-generation NVG, a gold-coated transparent sample (34 deg tilt) and its corresponding NVG-weighted spectral transmissivity plotted as a function of wavelength.

In order to determine how much an aircraft windscreen or canopy will reduce the light level by, it is necessary to measure or calculate the NVG-weighted transmission coefficient (T_{NVG}). This is done by using the spectral sensitivity of a given NVG[1,2,3]. Equation 1 describes the calculation for NVG-weighted transmissivity. T_{NVG} equals the integral with respect to wavelength, of the transparent part's spectral transmissivity [$P(\lambda)$] times the spectral energy distribution of the light source [$S(\lambda)$] times the NVG spectral sensitivity [$G(\lambda)$] divided by the integral with respect to wavelength, of the spectral energy distribution of the light source times the NVG spectral sensitivity. Since the specific spectral energy distribution of the light source in Equation 1 is typically not known for operational conditions (it depends on the spectral energy distribution of the illumination source on the scene and the spectral reflectivity of the various objects in the scene) the NVG-weighted transmission coefficient was calculated using $S(\lambda) = 1$ for all wavelengths. This simplifies the equation and typically does not significantly affect the results for the vast majority of broad-band reflectance distributions normally encountered. Figure 1 shows the spectral transmissivity curve for one of the gold-coated samples used in this study. The third-generation NVG sensitivity curve is plotted for reference.

$$T_{NVG} = \frac{\int_{450nm}^{950nm} P(\lambda)S(\lambda)G(\lambda)d\lambda}{\int_{450nm}^{950nm} S(\lambda)G(\lambda)d\lambda} \qquad (1)$$

where:

T_{NVG} = NVG-weighted transmissivity
$P(\lambda)$ = spectraradiometric scan through the transparent part
$S(\lambda)$ = spectral energy distribution of the light source (equal to 1 for our calculations)
$G(\lambda)$ = spectral sensitivity of the night vision goggle

Undocumented reports from some aircrew in different aircraft indicated that some transparencies, such as gold-coated F-16 canopies, may cause a reduction in NVG visual acuity compared to uncoated transparencies. Investigation into the NVG-weighted transmission level of currently fielded F-16 canopies revealed that there are at least three different gold coatings and two different indium-tin-oxide coatings in use. It was therefore the objective of this study to investigate the effect of coated transparent parts that included the full range of NVG-weighted transmission coefficients that might be found in the field. Since we could not obtain samples of all of the different types of coated windscreens it was decided to use what samples we did have in such a way as to provide a fairly wide range of transmissivities. Two gold-coated sections of transparencies were available: one with a fairly light coating and one with a relatively heavy coating. In order to expand the range even further, viewing through the heavily-coated sample was done at a tilted angle which made the transmission coefficient even smaller.

METHOD

Participants
The three participants in this study were not naive subjects in the traditional sense but highly trained psychophysical observers, two males and one female, ranging in ages from 35 to 46 years.

Apparatus and Stimuli
The tests utilized a new set of ITT Model F4949D (serial #3873) NVGs[4] that had P-43 phosphor image intensifier tubes and a measured gain[5] of about 6000. With the room lights off and the NVGs on, the observer first adjusted the interpupilary distance of the goggles. Then they adjusted the eyepiece lenses by looking at the dark ceiling with the goggles and focusing until the scintillation looked sharp. Objective lenses were focused by viewing a one-half moon illuminated, NVG resolution chart composed of square-wave gratings[6].

All observations were made in a lighttight room. The observer sat in a chair behind a table with their eyes 9.14 m (30 ft) from the stimulus easel. On the table was a fixture that held an aircraft transparency sample and a foam board visual field mask which had a 15 cm high by 18 cm wide (6 by 7 in.) aperture. The observer held the NVGs but could rest his or her elbows on the table while looking through the hole and transparency at the stimulus. The goggles were powered using a regulated external power supply.

The stimuli were Landolt C's[7] printed using a high resolution photo-grade laser printer. All of the C's (in each set) were consecutively numbered 1 through n for ease of use with the computer program (see *Procedure* section) during the study. After the study, the observers' data were converted to Snellen equivalents. The high contrast (70% Michelson) set consisted of 69 C's ranging from 20/19.1 to 20/200.5 Snellen acuity for the 9.14 m viewing distance. C's 1 through 48 increased by about 2 minutes-of-arc (MOA) per step and C's 49 through 69 increased in about 2 to 4 MOA steps in order to insure a high upper range. The low contrast (20% Michelson) set consisted of 107 C's ranging from 20/19.1 to 20/236.8 Snellen acuity. For this set, C's 1 through 92 increased by about 2 MOA per step and C's 93 through 107 increased in about 2 to 4 MOA steps. The first stimulus presentation, as determined by the program, was always from the center of the set's range and all subsequent thresholds were found to be below this value.

The C's were mounted on 18 x 18 cm (7 x 7 in.) foam board. The letter and background were different gray levels, varied to achieve the two desired contrasts but maintain the same average reflectance. For presentation, the C was placed onto a larger surround board 61 x 61 cm (24 x 24 in.) that matched either the high or low contrast Landolt C background reflectance as appropriate. The background board was held on an easel and had a small ledge that held the letter C in the center. The ledge was invisible when viewed through NVGs. The C was then easily placed onto the ledge with the gap oriented either up or down.

The experimenter's station was to the side of the stimulus easel. The computer's electroluminescent, backlighted liquid-crystal display was filtered and shrouded to eliminate any stray light from falling on the target pattern.

Three, precalibrated, 2856K incandescent lamps[8] were used to easily change to the different illumination levels. Apertures varied their intensity without affecting the color temperature. Illumination levels used were: 1x starlight = 3.4×10^{-4} lx (3.2×10^{-5} fc)[9]; 2x starlight = 6.7×10^{-4} lx (6.2×10^{-5} fc); 5x starlight = 1.8×10^{-3} lx (1.7×10^{-4} fc). A fourth lamp, set to about one-half moon illumination 1.3×10^{-1} lx (1.2×10^{-2} fc) was used to illuminate an NVG resolution target[6] during pretest goggle focusing.

Three transmission conditions were included in this study: a tilted heavily gold-coated sample, a non-tilted lightly coated sample, and no intervening transparency (100% transmission, hereafter termed baseline or high T_{NVG}). The T_{NVG} for the heavily gold-coated sample tilted to a 34 deg orientation was 58% (hereafter termed low T_{NVG}). The untilted (normal) lightly gold-coated sample had 76% transmissivity (hereafter termed medium T_{NVG}). This study used three different combinations of stimulus illumination, with three different levels of T_{NVG} coefficient to achieve nine total levels of equivalent illumination. Table 1 summarizes the nine equivalent illumination levels derived from the different illumination and T_{NVG} coefficient combinations.

Testing was conducted within randomized blocks of the lighting conditions because the observer had to adapt to that level before the test. First, an illumination source was randomly selected. Within that lighting level, the observer was tested with a randomized order of stimulus contrasts and transparency samples. Two levels of contrast (20 and 70%), three levels of illumination and three levels of T_{NVG} yielded nine experimental conditions for high contrast letters and nine experimental conditions for low contrast. The visual acuity through the NVGs for trained observers was measured as a function of these nine equivalent illumination levels.

Table 1. The nine different equivalent illumination levels produced by all combinations of the three levels of stimulus illumination and three levels of transparency T_{NVG} coefficients.

MULTIPLES OF STARLIGHT	LOW T_{NVG} coefficient T_{NVG} = 58%	MEDIUM T_{NVG} coefficient T_{NVG} = 76%	HIGH T_{NVG} coefficient T_{NVG} = 100 %
1x	0.58	0.76	1
2x	1.16	1.52	2
5x	2.9	3.8	5

Procedure

A portable computer executed a two-alternative, forced-choice Step Program adapted from Simpson[10]. The experimenter started the Step Program which asked for the initial setup parameters: Landolt C upper and lower stimulus identification numbers (1 through 69 for high contrast or 1 through 107 for low contrast), confidence level (95%), number to criterion (5), maximum total number of trials (50) and a data file name. Using a conservative 95% confidence level caused the program to require a few more trials before converging to threshold.

The proper stimulus surround was placed onto the easel, a 1x, 2x or 5x starlight lamp was energized and the transparency sample placed into the fixture. The observer then partially dark adapted to the goggle output luminance for about 10 minutes. The Step Program instructed the experimenter to place a given numbered (size) Landolt C in an up or down, randomized position. The stimulus was blocked from the observer's view by the experimenter during placement onto the easel. The experimenter asked the observer if he or she was ready, unblocked the stimulus for about 4 seconds, then blocked it again. The observer had to respond either "up" or "down". No feedback was ever given to the observer. The experimenter then removed the stimulus and entered the observer's response into the Step Program. Based on the response, the Step Program determined the next stimulus size and randomized its orientation. The procedure was repeated until criterion was reached or the maximum number of trials were met. All observers converged before reaching the maximum number of trials. This procedure averaged about 10 minutes per experimental condition with five minute rests after each condition and additional rest after completion of each lighting condition.

RESULTS

The study presented a total of 1015 stimuli to the three observers. Threshold criterion (5 correct responses at smallest, reliably seen gap size) was reached in 19 trials on the average, 10 being the fastest and 38 the slowest (see Fig. 2 for an example). Snellen acuity, which served as the dependent variable, was calculated from the viewing distance and the gap size of the Landolt C with the standard conversion that 20/20 Snellen acuity corresponds to a gap size of one minute of arc. Table 2 is a summary of the results for the high contrast Landolt C condition listing the Snellen acuity for each illumination/transparency combination for each trained observer and the average across observers. The equivalent illumination column is the fraction of starlight that was available to illuminate the target pattern after accounting for the transmission coefficient of the transparency. This value was calculated by multiplying the illumination level (1, 2, or 5 times starlight) by the transmission coefficient (0.58, 0.76, or 1.00) for each condition. Table 3 is a summary of the results for the low contrast condition.

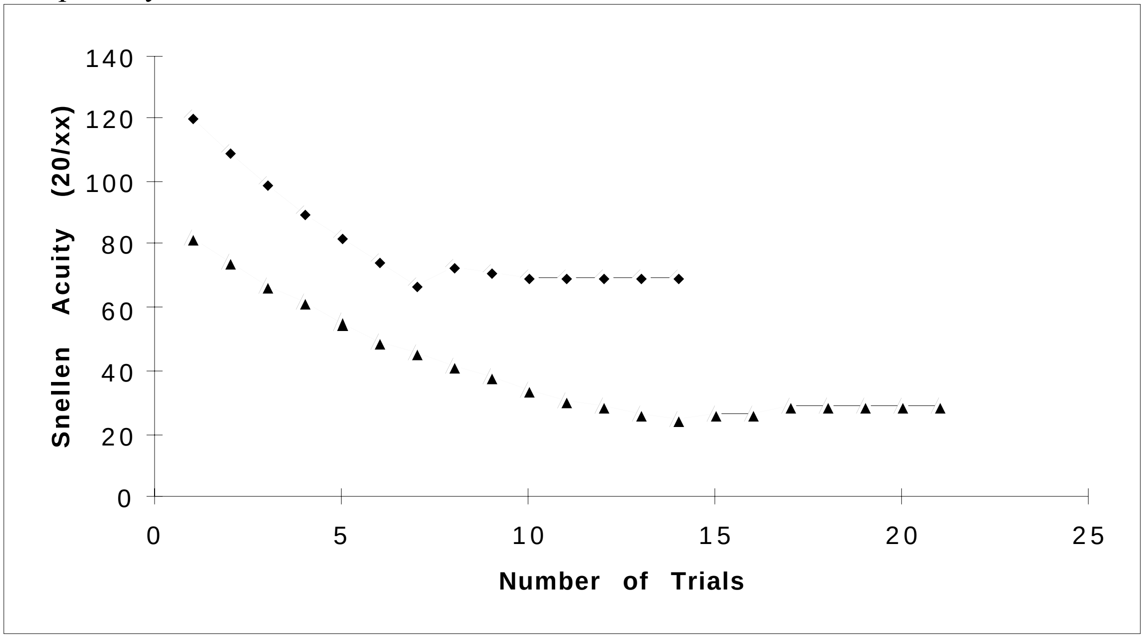

Figure 2. Typical Landolt C presentation sequences using the computer-based Step Program.

Table 2. Summary of high contrast (70%) stimuli data. All data are Snellen acuities (20/xx).

ILLUMINATION (X STARLIGHT)	T_{NVG} COEFFICIENT	EQUIV ILLUM	OBSERVER 1	OBSERVER 2	OBSERVER 3	MEAN
1x	LOW	0.58	66.8	63.0	61.1	63.6
1x	MEDIUM	0.76	61.1	59.2	49.7	56.7
1x	HIGH	1	53.5	51.6	47.7	50.9
2x	LOW	1.16	51.6	57.3	47.7	52.2
2x	MEDIUM	1.52	49.7	47.7	43.9	47.1
2x	HIGH	2	45.8	43.9	36.3	42.0
5x	LOW	2.9	36.3	40.1	36.3	37.6
5x	MEDIUM	3.8	36.3	32.5	34.4	34.4
5x	HIGH	5	36.3	32.5	34.4	34.4

Table 3. Summary of low contrast (20%) stimuli data. All data are Snellen acuities (20/xx).

ILLUMINATION (X STARLIGHT)	T_{NVG} COEFFICIENT	EQUIV ILLUM	OBSERVER 1	OBSERVER 2	OBSERVER 3	MEAN
1x	LOW	0.58	114.6	103.1	149.0	122.2

1x	**MEDIUM**	**0.76**	128.0	105.0	126.1	119.7
1x	**HIGH**	**1**	108.9	99.3	107.0	105.1
2x	**LOW**	**1.16**	114.6	84.0	122.2	106.9
2x	**MEDIUM**	**1.52**	112.7	108.9	82.1	101.2
2x	**HIGH**	**2**	105.0	99.3	70.7	91.7
5x	**LOW**	**2.9**	101.2	93.6	74.5	89.8
5x	**MEDIUM**	**3.8**	68.8	87.9	68.8	75.2
5x	**HIGH**	**5**	47.7	74.5	61.1	61.1

DISCUSSION

Although none of the combination of conditions (illumination and transmission coefficient) permitted a direct test of the equivalent illumination hypothesis, it was possible to graph the Snellen acuity results against the equivalent illumination to see if it would produce a reasonably smooth, monotonically decreasing curve. This is the type of curve that would be expected since, in general, visual acuity improves (Snellen acuity value is smaller) as light level to the eye increases[11]. Figures 3 and 4 show these graphs for the high contrast and low contrast conditions, respectively.

The graphs of Figures 3 and 4 include all of the individual observer data in addition to a dashed line that corresponds to the average for the three observers for each equivalent illumination condition. The high contrast graph of Figure 3 demonstrates a very clear pattern, although it is apparent that there is a certain amount of observer variability and differences between observers. Based on visual inspection of the graph in Figure 3, a curve fit was applied using a simple reciprocal model. The general form of the model equation was:

$$S = K + \frac{M}{E} \qquad (2)$$

where:

S = Snellen acuity (20/xx)
K = constant (empirically determined by least squares fit)
M = proportionality constant (empirically determined)
E = equivalent illumination

Table 4 is a summary of the model fit (Equation 2) for both the high contrast and low contrast Landolt C. The model is shown in Figures 3 and 4 as a solid line. The model fits reasonably well for the high contrast condition (r = 0.981) and not too badly for the low contrast condition (r = 0.912) given that human observations are involved. It should be noted that this fit was done for a relatively small range of illuminations (0.58 to 5.0 times starlight) and

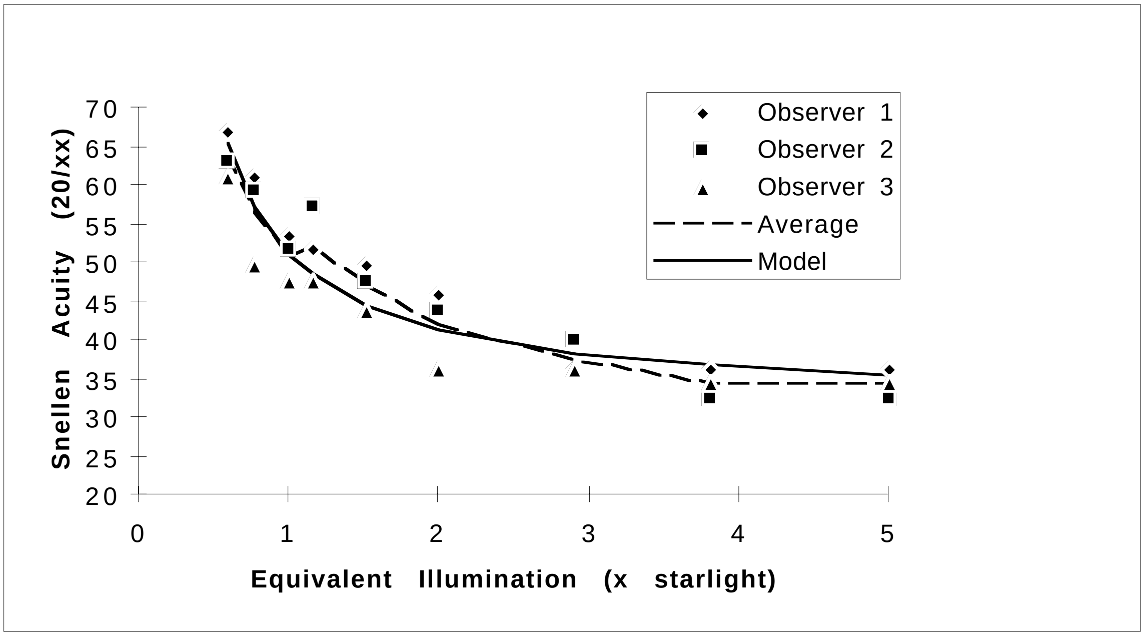

Figure 3. Plot of Snellen acuity as a function of starlight illumination for high contrast Landolt C stimuli (data from Table 2).

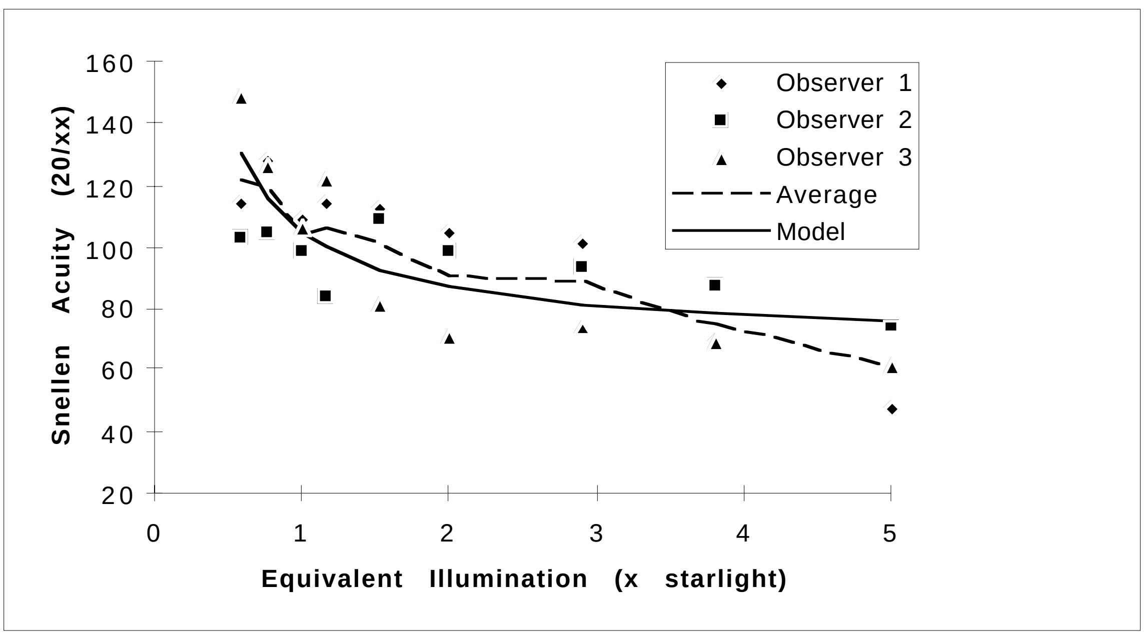

Figure 4. Plot of Snellen acuity as a function of starlight illumination for low contrast Landolt C stimuli (data from Table 3).

is therefore only valid for this range. It is possible the basic model (Equation 2) may still hold up for a greater range of illuminations but that has not yet been tested.

Table 4. Summary of model fit to data.

CONDITION	K	M	CORR (*r*)
70% CONTRAST	31.6	19.6	0.981
20% CONTRAST	70.0	35.3	0.912

The results shown in Figures 3 and 4 and the correlations in Table 4 support the validity of the hypothesis regarding using equivalent illumination and the T_{NVG} as a means of assessing the quality of aircraft transparencies with respect to NVGs. It is possible to use Equation 2 with the appropriate coefficients from Table 4 to reasonably predict the impact on visual acuity of a specific windscreen or canopy if its T_{NVG} value is known.

There is, however, an implicit assumption that must be addressed before applying the model presented herein. These results and the model presented assumes the transparency has a very low haze value[12]. Haze is a phenomenon caused by light scattering from materials within the transparency or from micro-scratches on the surface of the transparency (usually due to repeated cleaning). The effect of haze is to lower the contrast of objects viewed through the transparency which, in turn, would reduce visual performance (Snellen acuity). The implicit assumption was that the transparencies employed in this study had very little or no haze. The two transparencies used in this study were measured[13] and were found to have fairly low values of haze; 1.7% for the medium transmission and 2.4% for the low transmission transparency samples. If haze is present, then the model needs to be modified to include the loss in visual acuity due to contrast reduction. If haze is not present, then the contrast of objects viewed through a transparency remains the same no matter what the transmission coefficient is; only the apparent luminance of the object is affected. Future work in this area will address the haze issue.

REFERENCES

1. ASTM P94-02 (Draft). Night vision goggle compatibility of transparent materials. American Society for Testing and Materials Subcommittee F7.08 on Aerospace Materials.

2. ASTM F1316-90 (1991). Standard test method for measuring the transmissivity of transparent parts. *Annual Book Of American Society for Testing and Materials, 08.01.*

3. Task, H. L. and Merkel, H. S. (1989). A new method for measuring the transmissivity of aircraft transparencies. Technical Report AAMRL-TR-89-044, Armstrong Aerospace Medical Research Laboratory, Wright-Patterson AFB OH.

4. International Telephone and Telegraph (ITT), Roanoke VA.

5. Hoffman ANV-120 NVG Test Set. Hoffman Engineering Corp., Stamford CT.

6. Task, H. L. and Genco, L. V. (1986). Contrast sensitivity function measurement chart and method. US Patent # 4,607,923.

7. National Academy of Sciences (1980). Recommended standard procedures for the clinical measurement and specification of visual acuity. Report of Working Group 39, Committee on Vision. *Advances in Ophthalmology, 41,* 103-148.

8. MIL-L-85762A (24 Jan 1986). Night vision imaging system (NVIS) compatible interior aircraft lighting. Military Specification.

9. RCA Electro-Optics Handbook (1974). Technical Series EOH-11. RCA Solid State Division, Electro Optics and Devices, Lancaster PA, pp. 70, 75.

10. Simpson, W. A. (1989). The Step method: A new adaptive psychophysical procedure. *Perception & Psychophysics, 45(6),* 572-576.

11. Shlaer, S. (1937). The relation between visual acuity and illumination. *Journal of General Physiology, 21,* 165-188.

12. Task, H. L. and Genco, L. V. (1985). The measurement of aircraft windscreen haze and its effects on visual performance. Technical Report AFAMRL-TR-859-016, Air Force Aerospace Medical Research Laboratory, Wright-Patterson AFB OH.

13. ASTM F943-90 (1990). Standard test method for measuring halation of transparent parts. *Annual Book Of American Society for Testing and Materials, 08.01.*

ACKNOWLEDGMENTS

The authors gratefully acknowledge the help of Sharon Dixon and David Sivert of Logicon Technical Services, Inc. Sharon collected the data and performed the initial data reduction. David was responsible for the experimental setup and equipment calibration.

BIOGRAPHIES

ALAN PINKUS has been an Air Force psychologist since 1982. As a human factors engineer, he has worked on major systems including Royal Saudi Air Force KE-3 tanker, Gunship 2, LANTIRN, Air Force One and Joint-Stars. As a researcher, he has worked in the areas of image display metrics, night vision goggles, apparent motion, aircraft lighting, transparency analysis, vision from space, workload assessment and has lectured for NATO AGARD in Europe. Alan has a BS Degree (Wright State, 1974), an MA (University of Dayton, 1980) and a PhD (Miami University, 1992), all in Experimental Psychology. He holds seven patents (or pending) in the area of night vision goggle ancillary devices and has over 20 publications. He is a member of the Human Factors and Ergonomics Society (Southern Ohio Chapter), SAFE, Association of Aviation Psychologists and is active in the American Society for Testing and Materials Subcommittee F7.08 on Aerospace Transparencies.

H. LEE TASK has been employed as a research scientist for the US Air Force since 1971. He has served as chief scientist for the Armstrong Aerospace Medical Research Laboratory (prior to its reorganization and disestablishment in 1991) and is presently a senior scientist at the Visual Display Systems Branch of the Human Engineering Division, in the Armstrong Laboratory's Crew Systems Directorate, at Wright-Patterson AFB, Ohio. He is currently involved in research and development in the areas of helmet-mounted displays, vision through night vision goggles, optical characteristics of aircraft windscreens, vision, and display systems. He has a BS Degree in Physics (Ohio University), MS degrees in Solid State Physics (Purdue, 1971), Optical Sciences (University of Arizona, 1978), and Management of Technology (MIT, 1985) and a PhD in Optical Sciences from the University of Arizona Optical Sciences Center (1978). During his career he has earned 36 patents and has published more than 75 journal articles, proceedings papers, technical reports, and other technical publications. He is a member of the Human Factors and Ergonomics Society (HFES), the American Society for Testing and Materials (where he is chairman of Subcommittee F7.08 on Aerospace Transparencies and is a Fellow of the Society), the Association of Aviation Psychologists, SAFE association, the Society for Information Display (SID), and SPIE (the optical engineering society). He has served as reviewer for papers in SAFE, SID, and HFES.