ASC 91-2960

This article was originally published in 1992 in:
AGARD Lecture Series 187: Visual Problems in Night Operations (pp. 8-1 - 8-6). Neuilly Sur Seine, France: NATO Advisory Group for Aerospace Research & Development. (NTIS No. AGARD-LS-187)

COCKPIT/NVG VISUAL INTEGRATION ISSUES

H. Lee Task, Ph.D.
AL/CFHV
Armstrong Laboratory
Wright-Patterson AFB, Ohio 45433

INTRODUCTION

This paper is divided into two main sections: Visual significance of NVG characteristics and Cockpit/NVG integration issues. The first section deals with the relationship between the NVG characteristics discussed in the previous paper and visual capability. The second section explores several issues associated with successfully integrating the NVG with the aircraft cockpit for optimum system performance.

VISUAL SIGNIFICANCE OF NVG CHARACTERISTICS

Table 1 is a listing of the NVG parameters discussed in the previous paper paired with the visual parameter that it is most closely related to. Each of these is discussed in the following sections.

Table 1. NVG and vision parameters.

NVG PARAMETERS	VISION PARAMETERS
Field-of-view	Visual field
Image quality	Visual acuity
Exit pupil size	Eye pupil diameter
Eye relief	Eyeglasses
Image location (focus)	Accommodation
Luminance level	Brightness
Luminance gain	Visual acuity
Luminance uniformity	Image perception
Beamsplitter ratio	Image perception
Distortion	Image perception
Magnification	Binocular effects
Input/output align.	Binocular effects
Image rotation	Binocular effects
Fixed pattern noise	Masking/distraction
Signal-to-noise ratio	Visual acuity

Field-of-View

The visual parameter that corresponds to the NVG FOV is the human eye's visual field which is approximately 200 degrees horizontally and 120 degrees vertically (Wells et al, 1989). However, this is somewhat misleading since the visual acuity over this range is quite varied. Only the central 3-5 degrees provide high-acuity vision; the visual acuity drops off quite rapidly outside of this area. This means that for a 40 degree FOV NVG some of the resolution on the display is not being used by the visual system; but the "extra" FOV is important for providing peripheral vision information.

The total FOV may be increased by partially overlapping the two NVG oculars as noted in the previous paper. At least one study suggests that there is little performance difference between 100% overlap and 80% overlap for visual recognition performance (Landau, 1990) implying that an 80% overlap binocular NVG may be a good compromise between the need for larger FOV without impacting visual performance.

However, in real NVG oculars there are other factors that may produce undesirable binocular effects in the overlap region. If the oculars have a significant center to edge luminance non-uniformity then this could result in a binocular luminance imbalance for parts of the overlap image region. Barrel or pincushion distortion may not be noticeable for fully overlapped oculars but if they are only partially overlapped then the distortion may result in a mismatch between corresponding points in the two oculars (Self, 1986) producing binocular rivalry.

Image Quality

The visual parameter corresponding to image quality (resolution & contrast) is visual acuity. Normal visual acuity for the human eye is approximately one minute of arc for high contrast, brightly lit targets. However, this acuity is reduced for lower light levels such as those found in the NVG display (maximum of about 1 to 2 foot-Lamberts with typical operational luminances much lower). If one were to match the display image quality to the human eye, a first order design might result in a pixel on the display subtending an angle of one minute of arc. For an image source consisting of 500 by 500 pixels, this would mean an angular subtense of the entire display of 500 minutes of arc, or 500/60 = 8.3 degrees. While this NVG might result in good image quality to the human eye, it would be an extremely small display. Most NVGs provide a FOV that results in an angular resolution larger than one minute of arc suggested by human visual acuity.

Exit Pupil

When the eye pupil is fully within the exit pupil of the NVG then the entire FOV is observed; if the eye pupil is only partially in the exit pupil (and the exit pupil is unvignetted) then the observer will still see the entire FOV but it will be reduced in brightness. This can be particularly disconcerting for NVGs used in high performance aircraft because the pilot may not know whether he is starting to lose the exit pupil or if he is starting to lose consciousness from high acceleration maneuvers. Once the eye pupil is outside the exit pupil then none of the NVG FOV can be seen. It should also be noted that the NVG FOV may become vignetted (lose part of the image) if the eye pupil is too close to or too far away from the exit pupil.

From a visual capability standpoint it is important for the exit pupil to be as large as possible to ensure the eye pupil will remain within it to permit viewing of the NVG. However, large exit pupils typically come only at the expense of greater size of optics and weight on the head. In addition, if the FOV is very large then the eye must rotate to view the edge of the display. Since the eye rotates about a point within the eye, the eye pupil moves within the NVG exit pupil. If the NVG exit pupil is not large enough then it is possible for the entire display to disappear every time the observer tries to move his eyes to view the edge of the display. Exit-pupil-forming optical systems also increase the difficulty of making accurate adjustments for binocular or biocular NVGs in that each eye pupil should be centered in each exit pupil of the NVG.

Eye Relief

As with so many other NVG parameters, larger eye relief usually means larger and heavier optics. The reason for having a large eye relief is to allow the use of eyeglasses with the NVG (Self, 1973; Task et al, 1980). The eyeglasses may be for visual correction, eye protection or both.

Image Location

In order to obtain good image quality the eye lens must focus at the same optical distance as the virtual image produced by the eyepiece. For young eyes which have a fairly large accommodative range there is a tendency to set the focus (for NVGs that have eye-lens diopter adjustment) so that the image is too near. The image may look clear but long-term wear of the NVGs with the image at a close distance may lead to visual fatigue. For night operations it makes sense to have the NVG image focussed at the same distance as the aircraft panel instruments to minimize the time required to visually switch between looking at the NVG and looking at flight instruments.

Luminance Level

Brightness is the visual sensation or perception that corresponds to luminance. The luminance level has a significant effect on the pupil diameter of the eye; a higher light level means a smaller pupil diameter and vice versa. The visual acuity of the human eye also varies with eye pupil diameter (Farrell & Booth, 1984). However, for NVG applications the luminance must be kept reasonably low to match cockpit lighting levels for night operations. Thus the resolution observed on the NVG may well be a result of a combination of the inherent resolution of the NVG and the limits of visual acuity of the eye at low light levels.

Luminance gain

There isn't a direct visual analog to luminance gain. However, the higher the gain of an NVG for a given ambient lighting level then the higher the output luminance, which should result in higher visual acuity. A study by Levine and Rash (1989) stated that an 80% reduction in output luminance (equivalent to an 80% reduction in gain) by using a filter did not result in a statistically significant reduction in visual acuity. However, for starlight conditions their data showed a 37 percent reduction in visual acuity (not statistically significant) which is a rather substantial loss.

Luminance uniformity

Luminance uniformity is probably not a critical factor for visual performance or acceptance providing the luminance variation is gradual and not excessive. A ratio of 3:1 center to edge luminance variation in NVGs is not unusual. However, if the two NVG oculars are used in a partial overlap mode to increase the horizontal FOV then the luminance uniformity might be of more concern since this would produce a binocular luminance mismatch between the two eyes.

Distortion, image rotation, magnification, and input/output optical axes alignment

These four geometric mapping parameters are grouped together since, with the exception perhaps of distortion, they are all primarily a problem only for binocular systems. If a monocular image is slightly rotated, or slightly different from unity magnification or slightly shifted in position (optical axes alignment) it really doesn't affect the visual system. However, if the image in one eye is rotated relative to the image in the other eye at some point the amount of rotation is sufficient to cause the visual system to be unable to fuse the two images. This could result in double images or in suppression of one of the images. Similar effects occur if there is a mismatch between the two eyes due to distortion, magnification, or image position differences between the two oculars.

There may also be a less obvious effect due to geometric image mismatch. If the differences are not sufficient to cause image suppression or double imaging they still may be sufficient to cause eye fatigue, nausea, and or headaches when these slightly disparate images are viewed for a long period of time.

In addition, the distortion effects may produce undesirable illusions or image motion for dynamic viewing situations (such as landing).

These four parameters need to be specified based on their effects on binocular vision and not on their individual monocular effects.

Signal-to-noise ratio (SNR)

SNR primarily affects visual acuity. Riegler et. al. (1991) published a study showing the effect of SNR level on visual acuity for different luminance levels and contrasts using NVGs. Four PVS-7 image intensifier tubes were used that ranged in value from a SNR of 11.37 to 17.92. As might be expected the largest visual acuity differences were due to changes in contrast of the targets and light level. However, there was a significant effect due to the SNR of the tubes. The increase in visual acuity going from a SNR of 11.37 to 17.92 depended on the contrast and lighting conditions. For the low contrast (20%), low luminance (1% moon) the improvement in visual acuity was about 27% for the higher SNR tube. But for the high contrast (95%) high luminance (25% moon) the improvement was only about 10%.

Beamsplitter (combiner) ratio

The NVG beamsplitter (if one is used) is not designed to superimpose the NVG image on the real world scene but rather is intended to permit direct viewing of the aircraft HUD undegraded by the image intensifier system. This is accomplished by turning the NVGs off when viewing the HUD and turning them back on when viewing through the windscreen (the on/off switching is done automatically). But, as its name implies, the beamsplitter splits the light so that there is a reduction in luminance coming from the HUD (due to the transmission coefficient of the beamsplitter) and a reduction in luminance coming from the image intensifier (due to the reflection coefficient of the beamsplitter). In general the reflection and transmission coefficients must add up to a number less than one (assuming the beamsplitter coating is neutral with respect to wavelength). This results in a direct trade-off: higher transmission means the HUD will be easier to see but also means lower reflection coefficient, which results in a lower NVG scene luminance. For best results the beamsplitter probably cannot vary too much from a 50-50 split (same transmission and reflection coefficient).

Fixed pattern noise

This parameter primarily refers to the visible structure of the fiber optics twister or faceplate (if fiber optics is used in the image intensifier tube). The fiber optics production method results in a hexagonal pattern (also called "chicken wire" for this reason) that may become visible under higher lighting conditions. This acts as a distraction or masking pattern when trying to observe the NVG image. At present there is not a good means of quantifying this parameter and little data on the significance of this parameter with respect to visual performance. Typical specifications state that the "chicken wire" shall not be objectionable.

COCKPIT/NVG INTEGRATION ISSUES

Since NVGs do not attach to any part of the aircraft it is usually assumed (incorrectly) that there really are no integration issues. In fact there are several potential integration problems, a few of which are described herein.

Cockpit lighting

One of the earliest and most obvious NVG cockpit integration problems was the incompatibility of the NVGs with standard cockpit lighting. Most cockpit lighting is produced by incandescent bulbs filtered to produce red, white or blue-white lighting (depending on aircraft) for unaided night flying. The filtered incandescent lights, however, emit tremendous amounts of near infra-red energy to which the NVGs are very sensitive (700nm to 900nm). This produces considerable light pollution in the cockpit for the NVGs. The result is much like sitting in a well-lit room trying to look outside at night; the reflected light from the window is far greater than the meager light from outside coming through the window so one only sees the room reflections in the window instead of outside.

Several techniques have been developed to reduce or eliminate this problem (Holly, 1980; Task & Griffin, 1982; Mil Specification Mil-L-85762). These techniques include using filters to remove the near infra-red, using baffles to redirect the light away from the windscreen, and using alternate lighting sources such as electro-luminescent lighting (which has a very low infra-red component). It should be noted that just filtering the incandescent light and making it blue-green does NOT mean that the filter has removed the offending infra-red light. Many plastic filters that make the incandescent lighting appear blue-green are almost totally transparent in the 700-900 nm range so one must be careful in selecting filters for this purpose.

The phrase "NVG compatible" when referring to aircraft interior and exterior lighting has taken on at least two meanings. There is no question that the Mil-L-85762 lighting specification intent is to insure that the cockpit is illuminated with light that is visible to the unaided eye but is as invisible as possible to the NVGs. In the case of exterior lighting it is desirable to have lighting that is visible through the NVGs and to the unaided eye but insure that it does not "overpower" the NVGs.

Yet a third meaning of "NVG compatible" is for the light source to be visible ONLY to the NVGs and not to the unaided eye such as in aircraft landing lights for covert operations. Given these different interpretations of the phrase "NVG compatible" it is recommended that one be explicit in defining exactly what level of NVG visibility is desired.

Aircraft head-up display

Here again is another area in which "NVG compatible" is ill-defined. For some applications it may be desirable to be able to see the HUD image through the NVG image intensifier system (for non-beamsplitter NVGs) in which case one would like the NVGs to be able to "see" the light from the HUD. For other applications where the NVG has a combiner for viewing the HUD directly it is desirable to have the NVG be totally insensitive to the HUD image to prevent double imaging (direct view and NVG view). A further concern with some recent NVG designs is that the objective lens of the NVG may not be located in a position where it can see the HUD.

If the NVGs are to be used to view the HUD symbology then the symbol sizes need to be sufficiently large so that the resolution of the NVGs can still permit the pilot to easily read the symbols. This means the HUD symbol sizes should be absolutely no smaller that 20/60 (15 minutes of arc) and preferably larger.

Another issue of NVG and HUD compatibility is the transmission coefficient of the HUD combiner. The HUD image is produced by reflection from a combiner located directly in front of the pilot. This combiner therefore reduces the amount of light that is available for NVG viewing when looking through the combiner (even with the HUD off) due to the transmission coefficient of the combiner. The transmission coefficient may be 50% or less which means the scene viewed through the combiner will appear significantly darker that looking around the combiner. If the HUD is "on" it is even more difficult to view through the HUD due to the radiance of the HUD symbology.

Aircraft windscreen

There are several separate integration issues associated with the aircraft windscreen. The most obvious is the spectral transmission of the windscreen. Most windscreens are designed with the visible wavelengths (400-700nm) in mind. Some windscreens do absorb light in the very near infrared where the NVGs are most sensitive (700-900nm). This can significantly reduce the effective gain of the NVGs. Transmission coefficients for windscreens measured at their installed angle can range from 70% down to 20% or less depending on the aircraft and viewing angle through the windscreen. As the viewing angle is steeper (toward the lower, forward part of the windscreen) the percent transmission is lower. This is unfortunate since for many applications this is the part of the windscreen that is most critical for air-ground target acquisition and landing.

Another area of integration concern has to do with the aperture of the NVG objective lens. When a pilot views through a windscreen with unaided vision his eye pupil is on the order of 2 to 4 mm in diameter (daylight through early evening lighting). Thick, curved, plastic windscreens don't affect the pilot's visual acuity because his eye pupil is relatively small (ray bundle sizes are limited by the pupil). However, if a larger size aperture is used for imaging (such as an NVG objective lens) then the size of the windscreen over which the wavefront aberrations are averaged is larger and the potential for reduced clarity is greater. This is typically not a problem for flat glass or thin glass windscreens but for the more recent bird-strike resistant windscreens made of curved plastic it is a very real concern. The effect of the interaction on the larger NVG aperture with the windscreen is lower effective system resolution.

A third area of concern has to do with simple geometry. The NVGs protrude from the face by a considerable distance (as much as 8 inches). For small cockpits this can become a problem as pilots try to look out to the side where there is not much clearance with the windscreen. The NVGs can hit the windscreen causing scratches and not making the pilot very happy either.

Some NVG designs position the objective lens higher or further off to the side than the natural eye position. Windscreens are designed around a "design eye" and all optical quality measurements are made from this nominal viewing box. Since the NVG objective lens may be located at a significantly different position there may be a considerable decrease in optical quality due to the windscreen. In particular, if the objective lens is higher and therefore closer to the slanted windscreen, it will be looking through the windscreen at a steeper angle, which tends to reduce transmission and to enhance distortion effects.

BIBLIOGRAPHY

Brickner, Michael S., "Helicopter flights with night-vision goggles -- human factors aspects," NASA Technical Memorandum 101039, March 1989.

Department of Defense, Military specification*: Lighting, aircraft, interior, night vision imaging system compatible*, MIL-L-85762, Washington, DC 1986.

Farrell, R. J. and Booth, J. M., _DESIGN HANDBOOK FOR IMAGERY INTERPRETATION EQUIPMENT_, D180-19063-1, Boeing Aerospace Company, Seattle, Washington, reprinted February 1984.

Holly, F. F., "A night vision goggle compatible lighting system for Army aircraft," USAARL LR-

80-4-2-2, Fort Rucker, Alabama, 1980

Levine, Richard R. and Rash, Clarence E., "Visual acuity with AN/PVS-5A night vision goggles and simulated flashblindness protective lenses under varying levels of brightness and contrast," US Army Aerospace Medical Research Laboratory (USAARL), Fort Rucker, Alabama, report No. 89-16, July 1989.

Landau, Francine, "The effect on visual recognition performance of misregistration and overlap for a biocular helmet mounted display," in *Helmet-mounted displays II, Proceedings of SPIE 1290*, April 1990.

Lewandowski, Ronald J., Ed., *Helmet-Mounted Displays II, Proceedings of SPIE 1290*, April 1990.

McLean, William E., "Modified faceplate for AN/PVS-5 night vision goggles," US Army Aeromedical Research Laboratory (USAARL), Fort Rucker, Alabama, report No. 83-1, October 1982.

National Bureau of Standards, "Criteria for evaluating image quality of night vision devices," Report No. PB-257 171, August 1974.

Riegler, J. T., Whiteley, J. D., Task, H. L. and Schueren, J, "The effects of signal-to-noise ratio on visual acuity through night vision goggles," March 1991, AL-TR-1991-0011

Self, H. C., "The construction and optics problems of helmet-mounted displays," *in A symposium on visually coupled systems: development and application*, AMD TR-73-1, September 1973.

Self, H. C., "Optical tolerances for alignment and image differences for binocular helmet-mounted displays," AAMRL-TR-86-019, May 1986.

Task, H. Lee, "Optical and Visual Considerations in the design and specification of Helmet-Mounted Displays," Society for Information Display International Symposium Digest of Technical Papers, Vol XXII, pp297-300, Anaheim, California, May 6-10, 1991.

Task, H. L., Hartman, R., and Zobel, A., "New methods for night vision goggle test and evaluation," paper published in proceedings of Test Technology Symposium III held at Johns Hopkins University Kossiakoff Conference and Education Center, Laurel, Maryland, 19-21 March 1990.

Task, H. L. and Griffin, L. L., "PAVE LOW III: Interior lighting reconfiguration for night lighting and night vision goggle compatibility," *Aviation, Space, and Environmental Medicine*, pp1162-1165, December 1982.

Task, H. Lee, "An evaluation and comparison of several measures of image quality of television displays," AAMRL-TR-79-7.

Task, H. Lee, Kocian, Dean F., and Brindle, James H., "Helmet mounted displays: design considerations," in *Advancement on visualization techniques, Hollister*, W. M. (Ed.), AGARDograph No. 255, Harford House, London, October 1980.

Wells, M. J., Venturino, M., and Osgood, R. K., "Effect of field of view size on performance at a simple simulated air-to-air mission," in *Helmet-mounted displays, Proceedings of SPIE 1116*, March 1989.

Wiley, R. W., Glick, D. D., Bucha, C. T., Park, C. K., "Depth Perception with the AN/PVS-5 night vision goggle," USAARL report No. 76-25, July 1976.