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U.S. Army Research Institute
for the Behavioral and Social Sciences

Research Report 1622

Selective Factors Affecting Rotary Wing Aviator Performance With Symbology Superimposed on Night Vision Goggles

John W. Ruffner, Monty G. Grubb,
and David B. Hamilton
Anacapa Sciences, Inc.

July 1992

U.S. ARMY RESEARCH INSTITUTE
FOR THE BEHAVIORAL AND SOCIAL SCIENCES

A Field Operating Agency Under the Jurisdiction of the Deputy Chief of Staff for Personnel

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Research accomplished under contract for the Department of the Army

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Accesion For	
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Unannounced	☐
Justification	
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Distribution /	
Availability Codes	
Dist	Avail and / or Special
A-1	

DTIC QUALITY INSPECTED 3

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
1992, July

3. REPORT TYPE AND DATES COVERED
Interim Feb 91 - Dec 91

4. TITLE AND SUBTITLE
Selective Factors Affecting Rotary Wing Aviator Performance With Symbology Superimposed on Night Vision Goggles

5. FUNDING NUMBERS
MDA903-87-C-0523
62785A
790
1211
C03

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Anacapa Sciences, Inc.
P.O. Box 428
Fort Rucker, AL 36362-5000

8. PERFORMING ORGANIZATION REPORT NUMBER
ASI690-349-91

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Research Institute for the Behavioral and Social Sciences
ATTN: PERI-IR
5001 Eisenhower Avenue
Alexandria, VA 22333-5600

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
ARI Research Report 1622

11. SUPPLEMENTARY NOTES
Contracting Officer's Representative, Charles A. Gainer.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release;
distribution is unlimited.

12b. DISTRIBUTION CODE
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13. ABSTRACT *(Maximum 200 words)*

This report presents the findings of a review of the literature on night vision goggles (NVGs), head-up displays (HUDs), and helmet-mounted displays (HMDs). The review was conducted to identify factors affecting the performance of pilots using the NVG-HMD system that superimposes symbology on the NVG image. The perceptual and attentional problems associated with using NVGs, HUDs, and HMDs are well documented in the literature but are not well understood. The literature suggests that use of the NVG-HMD system is likely to result in several perceptual and attentional problems, most notably errors in distance estimation, inappropriate division of attention, and spatial disorientation. A coordinated program of research on the NVG-HMD system should be undertaken using laboratory simulation devices, flight simulators, and operational aircraft. Priority should be given to investigating the effects of variables that are identified as important in the literature review, and of practical significance to the Army and that have not been determined by design decisions.

14. SUBJECT TERMS
Attentional switching
Perceptual judgment
Head-up display
Helmet-mounted display
Symbology
Night vision goggles

15. NUMBER OF PAGES
69

16. PRICE CODE
--

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Unlimited

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std Z39-18
298-102

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Office, Deputy Chief of Staff for Personnel
Department of the Army

July 1992

Army Project Number
2Q162785A790

Human Performance Effectiveness
and Simulation

ACKNOWLEDGMENTS

The authors wish to express their appreciation to D. Michael McAnulty, Anacapa Sciences, Inc., and Dennis K. Leedom and Robert H. Wright, U.S. Army Research Institute Fort Rucker Field Unit, who reviewed and critiqued earlier versions of this report.

FOREWORD

The U.S. Army Research Institute Fort Rucker Field Unit is an operational unit of the U.S. Army Research Institute for the Behavioral and Social Sciences (ARI) and provides research support in aircrew training to the U.S. Army Aviation Center, Fort Rucker, Alabama. Research is conducted in-house and augmented by contract support as required. This report documents work performed for the MANPRINT Division under Task 1211, "Improving Crew and Team-Level Performance in Aviation and Ground Operations" and Work Unit 1211-C03 "Crew Performance Instrument Design" in support of an in-house research program on the Aviator Night Vision Imaging System Head-up Display (ANVIS-HUD).

During low-level night vision goggle (NVG) flight, it is difficult and potentially unsafe for aviators to divert their attention from the external scene to obtain critical flight information from cockpit instruments. The ANVIS-HUD, which superimposes flight symbology on the view obtained through the NVGs, has been proposed as a solution to this problem. The Army is engaged in an accelerated system test, acquisition, and fielding program to acquire the ANVIS-HUD for the UH-60A/L, OH-58A/C, UH-1V, AH-1F, and CH-47D aircraft. At a fully funded level, up to 600 units of the ANVIS-HUD system will be acquired over the next 5 years, representing an investment of approximately $150 million. However, many questions remain about the perceptual and attentional problems associated with using the ANVIS-HUD.

This report presents the findings of a literature review that identifies factors affecting the performance of pilots using the ANVIS-HUD system. The report concludes that superimposing symbology on the NVG is likely to result in perceptual and attentional problems that warrant investigation and recommends that a coordinated program of research be undertaken that addresses these problems.

It should be noted that the contractor conducting this review did not have access to some of the recent Army tests of proprietary prototype concepts for ANVIS-HUDs. Therefore, no reference to this testing is included in this report.

EDGAR M. JOHNSON
Technical Director

SELECTIVE FACTORS AFFECTING ROTARY WING AVIATOR PERFORMANCE WITH SYMBOLOGY SUPERIMPOSED ON NIGHT VISION GOGGLES

EXECUTIVE SUMMARY

Requirement:

During low-level night vision goggle (NVG) flight, it is difficult and potentially unsafe for pilots to divert their attention from the external scene to obtain critical flight information from cockpit instruments. One solution to this problem is to superimpose flight symbology on the view obtained through the NVGs, thus creating an NVG-Helmet-Mounted Display (HMD) system. The NVG-HMD may reduce workload by giving pilots access to flight information while they maintain visual contact with the external scene.

Although the NVG-HMD has several benefits, it may distract pilots' attention from the tasks of obstacle detection, recognition, and avoidance and interfere with NVG visual scanning patterns. Further, the NVG-HMD may contribute to errors in pilots' judgments of distance, altitude, and closure rates and to the tendency to become spatially disoriented.

Although some information is available on pilots' performance capabilities and limitations with NVGs, head-up displays (HUDs), and HMDs, little is known about the potential effects of adding symbology to the NVG. Further, there has been no attempt to integrate the available research findings on NVGs, HUDs, and HMDs to guide research on the NVG-HMD system. Therefore, the U.S. Army Research Institute Fort Rucker Field Unit requested that Anacapa Sciences, Inc., review the literature on the NVG-HMD system, identify the factors that affect the performance of pilots using the system, and identify the research issues.

Procedure:

Researchers conducted a review of the literature on the use of NVGs, HUDs, and HMDs. The purpose of the review was to summarize relevant findings in these areas and to identify issues that should be investigated in a program of research on the NVG-HMD system.

Findings:

The results of the literature review indicate that many of the perceptual and attentional problems associated with using NVGs, HMDs, and HUDs are documented but are not well understood.

With few research results available on HMDs and NVG-HMD system, little is known about the perceptual, attentional, and performance consequences of these devices.

NVGs are limited by low resolution and a narrow field of view (FOV). Pilots using NVGs can overestimate distances and underestimate closure rates, become spatially disoriented, and experience high levels of fatigue and workload. The performance capabilities and limitations of pilots using NVGs must be considered a part of evaluating the effects of adding an HMD. In addition, many factors affecting pilot performance with NVGs may interact with factors affecting pilot performance with HUDs and HMDs.

When pilots view the external scene through a collimated HUD, there is a tendency to overaccommodate to the symbology, which appears to be closer than the real world scene. Pilots have difficulty attending to both the HUD symbology and the real world scene and must switch their attention back and forth between the two. This may be due to cognitive influences on accommodation or to a requirement to process information in a serial rather than parallel manner. The ability to divide attention between two activities presented on the same display is likely to improve with practice.

When viewing both HUD symbology and a real world scene or a synthetic image, there is a tendency to fixate on one source of information. Thus, pilots experience difficulty detecting unexpected events in the symbology or the external scene, especially when the workload is heavy. The variables that affect attentional fixation are not well understood and should be investigated. However, it appears that attentional and cognitive factors are equally or more important than sensory and perceptual factors.

Many findings from HUD research, such as the difficulty pilots have dividing their attention between symbology and the external scene, may generalize to HMDs. However, the effects of many characteristics unique to HMDs (e.g., proximity to the pilot's eyes, attachment to the pilot's head and presence in the pilot's field of vision, and the potential for monocular or binocular symbology and imagery) should be investigated.

Informal evaluations of prototype NVG-HMD systems have reported that use of the NVG-HMD reduces workload and increases the safety of NVG flight. Most of the problems reported in the evaluations were attributed to improper fit, adjustment, or operation of the NVG-HMD system. Perceptual and attentional problems with the NVG-HMD were cited indirectly, possibly because few perceptual or attentional problems existed or because their effects were small relative to fit, adjustment, or operational problems.

A research program that investigates the effects of the NVG-HMD on distance estimation, event detection, and spatial orientation is recommended. The program should be a coordinated effort using laboratory simulation devices, flight simulators, and operational aircraft. Priority should be given to investigating the effects of variables that are identified as important in the literature review and of practical significance to the Army and that have not been determined by design decisions.

Utilization of Findings:

The results of the literature review should form a basis for planning and conducting a systematic program of research on the NVG-HMD system.

SELECTIVE FACTORS AFFECTING ROTARY WING AVIATOR PERFORMANCE WITH SYMBOLOGY SUPERIMPOSED ON NIGHT VISION GOGGLES

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GLOSSARY OF ACRONYMS AND ABBREVIATIONS

AN/AVS	Army Navy/Aviator Vision System
AN/PVS	Army Navy/Pilot Vision System
ANVIS	Aviator Night Vision Imaging System
CRT	Cathode Ray Tube
FLIR	Forward Looking Infrared
FOV	Field of View
H	Horizontal
HDD	Head-Down Display
HMD	Helmet-Mounted Display
HUD	Head-Up Display
m	Meter
MS	Millisecond
NASA-TLX	National Aeronautics and Space Administration Task Load Index
NOE	Nap-of-the-Earth
NVG	Night Vision Goggles
PNVS	Pilot's Night Vision System
s	Second
STRATA	Simulator Training Research Advanced Testbed for Aviation
SWAT	Subjective Workload Assessment Technique
TRS	Training Research Simulator
V	Vertical
VFR	Visual Flight Rule

SELECTIVE FACTORS AFFECTING ROTARY WING AVIATOR PERFORMANCE WITH SYMBOLOGY SUPERIMPOSED ON NIGHT VISION GOGGLES

Introduction

Army doctrine requires that helicopter pilots perform many night missions at terrain flight altitudes using night vision goggles (NVGs), a binocular night vision device that amplifies available light. Night terrain flight with NVGs, especially in the nap-of-the-earth (NOE) mode, is very demanding and often results in a high level of individual workload that is fatiguing. During night NOE flight with NVGs, it is difficult and potentially unsafe for aviators to divert their attention from the external scene to get flight information from cockpit instruments (Department of the Army, 1988; Simmons, Kimball, & Hamilton, 1985).

The most recent version of the NVGs requires the pilot to view cockpit instruments by looking under or around the goggles. However, reading instruments that differ in illumination and optical distance from the external scene is time-consuming and difficult. Therefore, pilots often must rely on verbal information from the copilots about the aircraft status while maintaining their attention on the external scene. This procedure requires a high level of cooperation and coordination by flight crews and increases crew workload.

To address this problem, the U.S. Army is considering superimposing flight symbology (e.g., altitude, heading, airspeed) on the NVG image. This combination is similar to the head-up display (HUD) that projects symbolic information on a combiner glass allowing the pilot to view both the symbology and the external scene simultaneously. The superimposed imagery and symbology will be displayed on a surface mounted to the pilot's helmet, thus creating a type of helmet-mounted display (HMD). This system is referred to as the NVG-HMD in this report.[1]

The NVG-HMD system has several potential benefits. The **pilots can access critical flight information without**

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[1]Although the popular literature sometimes refers to the system as the NVG-HUD, the term NVG-HMD is more descriptive and, therefore, is used in this report.

redirecting their gaze from the NVG image of the real world[2] scene to the instrument panel, and overall workload may be decreased. However, the NVG-HMD symbology may inappropriately distract the pilots' attention from obstacle detection, recognition, and avoidance, and may interfere with proper visual scanning patterns. The NVG-HMD symbology may also affect the pilots' judgments of distance, altitude, and closure rates and increase their tendency to become spatially disoriented.

Objective

The NVG-HMD system was developed from several technological advancements, most notably NVGs, HUDs, and HMDs. Although a considerable amount of information is available on pilots' performance capabilities and limitations with NVGs, HUDs, and HMDs, little is known about the potential effects of adding symbology to the NVGs. Furthermore, the available research findings on NVGs, HUDs, and HMDs have not been integrated to guide research on the **NVG-HMD system. Therefore, the U.S. Army Research Institute Field Unit at Fort Rucker, Alabama, requested that Anacapa Sciences, Inc., review the literature pertaining to the NVG-HMD system, identify the factors that affect the performance of pilots using the system, and identify the research issues. This report summarizes the results of the literature review.**

Organization of the Report

This report is organized into eight sections. The next section provides background information on physiological optics for readers who do not have a background in visual perception. The third section describes the NVGs and discusses relevant research. The fourth section discusses research on HUDs that is important for understanding the NVG-HMD system. The fifth section discusses research on HMDs and summarizes the results of research on three prototype NVG-HMD systems. The sixth section summarizes relevant research on perceptual judgement and attentional switching. The seventh section presents the conclusions drawn from the literature review. The final section proposes recommendations for research.

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[2]Throughout this report, the term real world is used to differentiate the actual external, outside-the-cockpit visual scene from that depicted by an image of the real world scene on a panel-mounted display, HUD, or HMD.

Physiological Optics

A basic understanding of physiological optics and associated perceptual phenomena is necessary for understanding the capabilities and limitations of the NVG-HMD system. Therefore, selected topics in physiological optics and visual perception are discussed briefly in this section. The overview is taken primarily from TC 1-204 Night Flight Techniques and Procedures (Department of the Army, 1988) and Coren and Ward (1989).

Light, Lenses, and Acuity

Humans are sensitive to a small part of the electromagnetic spectrum, ranging from approximately 400 nanometers (violet) to 700 nanometers (red). Three important characteristics of light are illumination, luminance, and reflectance. Illumination is the amount of light that strikes a surface from a source. Luminance is the amount of light per unit area reflected from a surface. Reflectance is the ratio of the amount of light reflected from the surface to the amount of light reaching the surface.

Contrast is a measure of the difference in luminance between an object and its background. Contrast increases when the difference in luminance between an object and its background increases. Contrast sensitivity refers to the perceptual ability to distinguish adjacent areas that differ in luminance.

Light entering the eye is bent, or refracted, by the cornea and the lens and falls on the retina, a membrane covering the inner surface of the eye. The cornea performs most of the refraction. However, an additional amount of refraction is required to focus light rays on the retina that emanate from objects at different distances. Accommodation is the process by which the lens changes shape to focus light on the retina. The closer the object, the more the lens has to accommodate to refract light.

The refracting power of the lens is measured in diopters, which is the reciprocal in meters (m) of the lens' focal length. A lens that has a focal length of 1.0 m has a diopter value of 1.0. A lens that has a focal length less than 1.0 m has a diopter value greater than 1.0. Conversely, a lens that has a focal length greater than 1.0 m has a diopter value less than 1.0.

The accommodative capacity of the lens may be insufficient to bring an object into focus. This results in different types of refractive or focusing errors. An individual who is farsighted (hypermetropic) can see far objects clearly but near objects are blurred on the retina, resulting in a loss of acuity (i.e., the ability to detect fine detail). In comparison, an individual who is nearsighted (myopic) can see near objects clearly but far objects are blurred. An individual who is slightly myopic may experience a decrease in acuity at night, which is known as night myopia.

When an individual looks at a visual scene that lacks detail, there is a tendency for accommodation to relax to an intermediate or resting level. In most individuals, this distance is approximately 1 m. Dark focus is a similar situation that can occur under low levels of illumination. There are differences in the nearest and farthest point to which an individual can focus and the resting level of accommodation.

Visual Receptors

The retina contains two types of light-sensitive cells: rods and cones. Cones concentrate in the central part of the retina called the fovea. They operate under relatively high levels of illumination and mediate higher levels of visual acuity than the rods. Cones respond differently to different wavelengths of light and mediate our perception of color. The color that we perceive depends, in large part, on the distribution of wavelengths in the light source and the characteristics of the reflecting surface. Light sources containing only a small number of wavelengths are called monochromatic.

The rods concentrate in the periphery of the retina, operate under relatively low levels of illumination, respond to changes in luminance but not wavelength, and play an important role in motion detection. Rod-mediated vision has poorer acuity than cone-mediated vision. During darkness, visual acuity decreases as the level of illumination decreases and rods mediate visual perception.

The visual field is the area in space from which visual information stimulates the two eyes. Visual information from the left visual field stimulates the right half of each retina and primarily projects to the right hemisphere of the brain. Visual information from the right visual field stimulates the left half of each retina and primarily projects to the left hemisphere of the brain. A number of cross-hemisphere connections, however, provide some representation of the ipsilateral visual field in each hemisphere.

Modes of Vision

Different ambient light conditions bring about three modes of vision: photopic, mesopic, and scotopic. Photopic vision functions under high levels of illumination during which the cones are operating. High visual acuity and color sensitivity are characteristic of photopic vision. Mesopic vision functions at moderate light levels (e.g., dawn, dusk, and full moonlight). Both the rods and cones operate during mesopic vision. Scotopic vision functions under low light levels. During scotopic vision, the cones become ineffective, resulting in poor acuity and loss of color vision. NVG viewing involves both mesopic and scotopic vision.

During dark adaptation, the eyes increase their sensitivity to low levels of illumination. Dark adaptation results from the shift from photopic, or cone-mediated vision, to scotopic, or rod-mediated vision. Most of the increase in sensitivity occurs within the first 30 minutes of dark adaptation, although additional increases in sensitivity occur up to 45 minutes.

Visual Angle

Visual angle is a measure of the size of an object's image that is projected on the retina. The object viewed is said to subtend a given visual angle which is usually expressed in degrees and minutes or milliradians.[3] As the object moves closer, the visual angle increases; conversely, as the object moves farther away, the visual angle decreases.

Field of View

Field of view (FOV) refers to the size of the visual area that can be seen with the human eye or with a sensor at one time. During normal viewing conditions, each eye has a

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[3] There are 360° in a circle, 60 minutes in 1°, and 60 seconds in 1 minute. One degree equals approximately 17.5 milliradians.

FOV of about 120° vertical (V) x 150° horizontal (H). With both eyes, the FOV increases to about 120° V x 200° H, with a fair amount of overlap (Verona & Rash, 1989). The FOVs of NVGs, HUDs, and HMDs are smaller than the FOV of the unaided eye. For example, the NVGs provide a circular FOV of 40°, whereas the FOVs of some HUDs may be as small as 12° H. High detail form vision is restricted to about 1° at the central fovea. The more peripheral visual fields are sensitive to visual flow from self-motion, object motions, and flashes.

Perception of Distance and Depth

Several sources of information or cues in the visual environment influence our judgment of distance and depth. The cues can be classified as monocular, those requiring only one eye to be effective, and binocular, those requiring both eyes. Examples of pictorial monocular cues (i.e., those available in pictures, drawings, and photographs) are interposition, relative size, linear perspective, motion perspective, texture gradient, shadowing, relative brightness, aerial perspective, and relative motion.

Accommodation is another monocular depth cue. Because the lens in the eye can focus only at one distance at a time, some objects are focused while others are blurred. Thus, objects in focus are judged to be at a different distance than blurred objects. The cue is described as ancillary and is not thought to be very powerful by most researchers. However, some researchers (e.g., Iavecchia, Iavecchia, & Roscoe, 1988; Roscoe, 1984; 1985; 1987a; 1987b) regard it as a potential major accident causal factor.

Binocular cues. Certain characteristics of human vision exist because our two eyes have a horizontal separation of about 65 millimeters (mm). Thus, the eyes receive slightly different images. This provides the basis for the depth cue of binocular disparity or stereopsis.

Another binocular depth cue is convergence. Convergence is the turning inward of the eyes on their vertical axis. Because the best visual acuity is obtained when an image is on the fovea, our eyes move to bring the image to the fovea. When an object is near, both eyes must rotate inward to accomplish this for both foveas. The eyes converge when looking at a near object and diverge when looking at a far object. There is evidence that the mechanisms for convergence and accommodation are closely linked and together they provide accurate depth information.

Modes of Presentation

Natural viewing involves the simultaneous use of both eyes, with each eye receiving a slightly different image. NVG, HUD, and HMD display systems use modes of presenting visual information that differ from natural viewing conditions. NVGs present binocular images on two displays that are mounted to the helmet only a few centimeters from the eyes. HUDs present symbolic information on a combiner glass located a few feet in front of the pilot. HMDs present different combinations of monocular or binocular symbology or imagery on a combiner glass located only a few centimeters from the pilot's eyes. For example, the AH-64A Helmet Display Unit presents both imagery and symbology to the pilot's right eye. The NVG-HMD presents imagery to both eyes and symbology to one eye. All the display devices collimate the images to optical infinity (i.e., greater than 50 m).

Collimation. Collimation is a procedure by which light rays are adjusted so near objects, such as NVG, HUD, or HMD displays, are located at optical infinity. Collimation eliminates the need for the pilots to reaccommodate as they shift their gaze back and forth between symbology and the real world scene because both are located at the same apparent distance.

Binocular rivalry. In normal binocular viewing, the brain fuses the images from the two eyes into one common percept. If the images are not markedly different, the brain uses the disparity between the two eyes' images as a cue for depth. However, when the images are markedly different, such as with the AH-64A Helmet Display Unit or the NVG-HMD, binocular rivalry occurs. One image becomes perceptually dominant while the other is suppressed, with alternations of dominance and suppression lasting between 1 - 4 seconds (s) occurring between the two eyes or between different parts of the left and right eye images.

The factors affecting dominance and suppression are complex; however, an image with high contrast and much detail will usually dominate (longer and more frequent periods of domination) an image with low contrast and little detail. Although individuals may prefer one eye over the other for better acuity or performance on sighting tasks during monocular viewing (Porac & Coren, 1976; 1986), total dominance of one eye for extended periods is rare (Arditi, 1986; Beaton, 1985).

Night Vision Goggles

NVGs are binocular night vision devices that increase nighttime visual capabilities by enhancing available light. This section is divided into four subsections. The first subsection summarizes the characteristics of the NVG system and is based primarily on the literature of Brickner, (1989b), Price and McLean (1985), and Verona and Rash (1989). The second subsection discusses NVG factors that degrade vision. Subsections three and four discuss illusions and misperceptions that often occur when wearing NVGs, especially the tendency to become spatially disoriented.

System Characteristics

The NVG system consists of two image intensifier tubes and the hardware required to mount and position the tubes on the pilot's helmet (see Figure 1). A lens on the far end of the NVG intensifier tube (the objective lens) focuses light on a sensor. Another lens on the near end (the ocular lens) allows pilots to see the viewing screen at infinity focus and to adjust for individual differences in refractive error. A diopter setting in the near lens can be adjusted from +2 to - 6 diopters.

The objective lens focuses light entering the intensifier tube onto a photocathode which is sensitive to both visible and near infrared radiation (see Figure 2). The light striking the photocathode causes a release of electrons in proportion to the amount of light. The released electrons are multiplied in a microchannel plate of small glass tubes before striking a phosphor screen. The number and velocity of the electrons striking the phosphor screen determine the amount of light produced by the system. The result amplifies the intensity of the image. The display image on the viewing screen is collimated to infinity.

Each intensifier has an automatic gain control that adjusts the tube's sensitivity to differences in ambient illumination levels. The automatic gain control protects the electron multiplier from extensive firing and damage from exposure to high light levels.

The first NVGs used by Army pilots, the Army Navy/Pilot Vision System (AN/PVS-5), were originally designed for ground vehicle operators. The AN/PVS-5 uses second-generation image-intensifier tubes and includes a full faceplate that obscures most of peripheral vision. Compared to natural

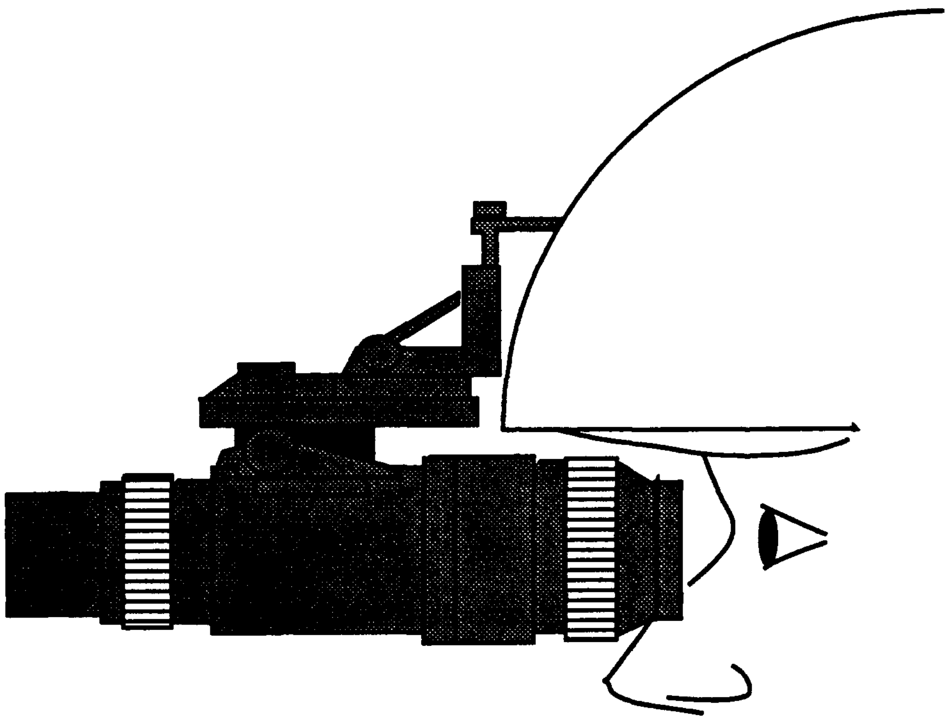

Figure 1. Night vision goggles.

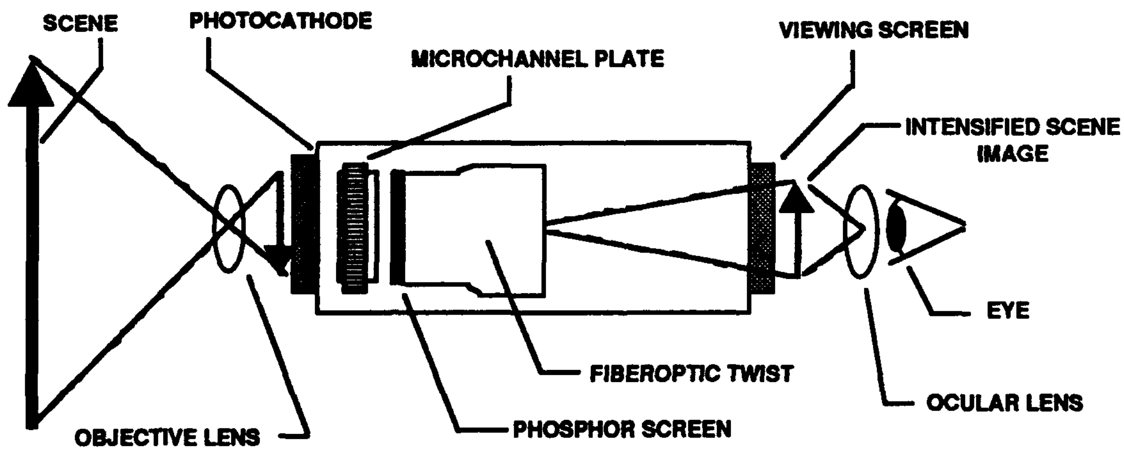

Figure 2. Schematic representation of an NVG image intensifier tube.

viewing conditions, the system has limited resolution and FOV. Under optimal conditions (i.e., high brightness and contrast), the best visual acuity obtainable is 20/50. Resolution with the AN/PVS-5 is best in the center of the FOV and decreases in the periphery. When the AN/PVS-5 is properly fitted close to the eyes, it provides a circular 40° FOV. The image viewed through the AN/PVS-5 has the same 1:1 magnification as when viewing with the unaided eye.

A modified version of the AN/PVS-5 was developed using a cutaway faceplate that obscured much less peripheral vision than the full faceplate. This change allowed the NVGs to be mounted to the helmet and flipped up when not in use. However, if the NVG tubes are moved away from the eyes to look under them, the circular 40° FOV decreases and the pilot loses the periphery of the image.

The Army has recently developed a new generation of NVGs, the Army Navy/Aviator Vision System (AN/AVS-6), known as the Aviator Night Vision Imaging System (ANVIS). The ANVIS, illustrated in Figure 1, uses third-generation intensifier tubes and operates in a similar manner to the AN/PVS-5. It has the same 40° FOV as the AN/PVS-5 but is more sensitive to red and near-infrared light that is characteristic of nighttime illumination. The ANVIS has greater sensitivity, slightly improved central and peripheral resolution, and weighs less than the AN/PVS-5. Although the improved resolution of the ANVIS provides 20/40 acuity under ideal conditions, acuity usually decreases under field conditions. Tredici and Miller (1985) found that acuity under starlight conditions dropped to less than 20/80 with the ANVIS.

Although both monocular and binocular cues are available for judging distances with unaided vision, the cues available for judging distances with the NVGs are primarily monocular. According to Wiley (1989), NVGs essentially eliminate stereopsis, causing NVG depth perception to be similar to monocular vision. However, having two independent images improves perceived brightness and contrast and reduces visual noise (Verona & Rash, 1989).

NVG Factors That Degrade Vision

NVGs degrade pilots' visual capabilities, most notably acuity and depth perception. Six commonly cited factors that degrade visual capabilities are intensifier tube deficiencies, inappropriate focusing, instrument myopia, night myopia, degraded visual cues, and limited FOV.

Although the following paragraphs discuss the individual influence of the factors, they may interact to degrade pilots' visual capabilities in ways that are not well understood.

Intensifier tube deficiencies. The NVG light intensifier tubes lose their sensitivity to light as they age. Because the tubes can be replaced independently, one failed tube can be replaced before the other, resulting in one tube being brighter. Moreover, the brightness is not adjustable. Differences in brightness between the two tubes can cause depth and movement illusions or suppress the image from one of the eyes. This, in turn, may result in a monocular rather than a binocular image. Suppression of one of the images can also occur if the tubes are misaligned (Brickner, 1989b).

Inappropriate focusing. Each NVG tube can be focused independently. However, failure to focus the NVGs properly for each eye individually and then for the two eyes together may result in the eyes accommodating to a nearer distance than infinity. The resulting overaccommodation (focusing too close) can cause eyestrain or blurred vision.

Instrument myopia. Pilots usually perceive objects seen through NVGs as being farther away or smaller than they actually are. Brickner (1989b) attributes this misperception to instrument myopia, which is the persistent state of overaccommodation while looking through an optical instrument (Hennessy, 1975). The reasons for instrument myopia are not completely understood. It may result from the tendency of the lens of the eye to assume an intermediate resting state without an adequate stimulus for accommodation.

When an individual overaccommodates during instrument myopia, a negative diopter setting on the NVGs may be required to focus the image. This overaccommodation indicates a misperception of depth that may result in inaccurate judgment of the size and distance of objects in the visual scene (Brickner, 1989b).

Roscoe (1985) noted that optically and sensor-generated computer-animated displays that present synthetic images of the world produce systematic errors in size and distance judgments. Objects are usually judged to be smaller and farther away than they actually are and must be magnified for objects to appear at the correct distance. Roscoe's research suggest that pilots using NVGs are likely to overestimate the distance of objects.

Night myopia. A visual phenomenon related to instrument myopia is night myopia. Night myopia is a condition in which an individual with normal day vision experiences myopia at night. Leibowitz and Owens (1975) described night myopia as the tendency to overaccommodate for distant objects as luminance is decreased. The overaccommodation results from the lens returning to a resting or dark focus position. The resulting accommodation is a compromise between the individual's idiosyncratic resting focus and that required by the stimulus. Accommodation becomes progressively biased toward the dark focus as decreased luminance degrades the adequacy of the accommodative stimulus.

Degraded visual cues. Even when pilots focus NVGs properly, estimating the size and distances of objects accurately is difficult because NVGs degrade the monocular visual cues normally available for estimating size and distances. The NVG image lacks variations in color and reduces variation in shade, detail, and texture, which are important perspective distance cues. During daylight, objects with poorer detail or texture and objects whose normal colors appear washed out and bluish-gray are perceived as being farther than objects with finer texture and vivid color. The loss of image resolution is considered one of the major factors that causes errors in distance estimation.

Limited field of view. The 40° circular FOV provided by the NVGs reduces the number of objects visible at one time. With fewer objects visible, pilots are less able to use the relative size of known objects as distance cues. Pilots are less likely to see as much object overlap, or interposition, as with a wider FOV. Weintraub (1987) proposed that a narrow FOV produces a framing effect in which objects inside the frame are perceived as smaller than their actual size.

With a narrow FOV, the pilot also loses some of the streaming effect (motion perspective) from objects passing out of sight in the periphery. Streaming is considered an important cue for spatial orientation and for perceiving speed of movement and closure rates. It is most effective at off-angles to the direction of motion and least evident in the direction of motion. By attending to the external scene straight ahead, the pilot may overestimate the distance of objects and underestimate closure rate (Brickner, 1989b).

Roscoe (1984) required student observers to adjust the magnification of a periscope with a 30° square FOV so objects viewed through the periscope were the same apparent size as when viewed directly. On the average, the observers magnified the periscope image approximately 1.2 times.

Roscoe's results suggest that errors in judging distances with a limited FOV may occur because of the loss of foreground texture, an important cue for estimating distance.

Foyle and Kaiser (1991) obtained distance estimates from four Army helicopter pilots under seven different viewing conditions: day unaided, day unaided with 40° circular FOV, night unaided, night unaided with 40° circular FOV, AN/PVS-5, ANVIS, and the AH-64A pilot's night vision system (PNVS), which has a 40° H by 30° V FOV. Two of the four pilots overestimated distances and two underestimated distances across all viewing conditions. The researchers' results did not support the commonly reported finding that distances are overestimated with NVGs.

The size of the NVG FOV has also been found to affect the accuracy of aviators' judgements of ground speed. For example, Armstrong, Hofmann, Sanders, Stone, and Bowen (1975) found aviators' ground speed judgments with NVGs were closer to the judgments obtained with the unaided eye when the NVG FOV was 60° rather than 40°.

Illusions and Misperceptions

The factors discussed above, both alone and in combination, may result in several types of misperceptions when using NVGs. Many of these problems have been reported during unaided night flight and are described in TC 1-204, Night Flight Techniques and Procedures (Department of the Army, 1988). Seven misperceptions that occur during normal night flight and that may be increased by the use of NVGs are summarized in Table 1.

Little research literature is available that documents the frequency of illusions and misperceptions with NVGs. Crowley (1991) conducted a survey of 221 pilots with NVG experience and identified several perceptual problems associated with using NVGs. The most frequently reported problems were (a) undetected aircraft drift (18%), (b) illusory aircraft drift (14%), (c) faulty height judgment (16%), and (d) disorientation (12%). However, the influence that NVGs have on these percentages cannot be determined because the researchers did not measure the incidence of the illusions during unaided night flight.

Table 1

Nighttime Illusions and Misperceptions

Illusion/ misperception	Description
Autokinesis	An illusion of movement caused by staring at a stationary light source in a dark environment
Illusory motion	An illusion of movement brought about by lights believed to be stationary (e.g., another aircraft) beginning to move
Height misperception	Judging the aircraft to be higher than it actually is above the terrain
Fixation	Stopping a normal scan pattern and directing attention to an outside object or on an instrument display
Size-distance	Interpreting a light source that is increasing or decreasing in size as approaching or retreating
Reversible perspective	Judging another aircraft to be moving away when actually approaching
Confusion of lights	Confusing ground lights with stars or with lights from another aircraft

Spatial Disorientation

Aviators using NVGs are likely to experience spatial disorientation. Spatial disorientation occurs when a pilot has an erroneous sense of the aircraft's position relative to the ground (Gillingham, 1990). It is thought to result from a conflict between vestibular cues (as the pilot experiences the motion of the aircraft) and visual cues (as the world visually appears to be moving). Because of the limited NVG FOV, pilots must use frequent head and eye movements to scan the external environment. Adopting a proper scanning pattern is very important for effective use of NVGs (e.g., Department of the Army, 1988); improper scanning has been cited as a major contributor to NVG accidents among Army aviators (U.S. Army Safety Center, 1991). If the head is moved too rapidly while scanning, spatial disorientation may result (Brickner, 1989b; Price & McLean, 1985). Pilots using NVGs are cautioned to rotate their heads and to move their eyes slowly in a continuous scan pattern to avoid disorientation.

In addition to rapid head movement while wearing NVGs, the loss of object detail and the restricted NVG FOV may cause spatial disorientation. Spatial disorientation may be more likely when critical details of the visual scene are lost or when the pilot transitions from visual to instrument flight conditions and has not begun a full instrument scan (Vyrnwy-Jones, 1988).

Head-Up Displays

The HUD is a collimated display in the pilot's forward FOV that projects flight symbols on a combiner glass between the aviator and the aircraft windshield. The HUD simultaneously projects onto the retina both the distant real world scene and the superimposed flight symbology. An example of a HUD is shown in Figure 3. Because the NVG-HMD system can be considered a HUD that is attached to the NVGs, the characteristics of HUDs are discussed and research on pilot performance with HUDs is reviewed before discussing HMDs.

HUDs were developed in the 1950s as an aid to pilots of high-performance fixed wing aircraft flying under visual flight rule (VFR) conditions. The first HUD-type displays were crude World II gun and bombing sights and a few aids for making approaches. However, the potential application of HUDs to other mission phases and to rotary wing aircraft subsequently led to a variety of design formats (Egan & Goodson, 1978).

Section 3.5 of MIL-D-81641 (AS) (Department of Defense, 1972) contains the design specifications for HUDs. According to Egan and Goodson, most of the specifications are based on expert opinion rather than empirical research. The specifications serve a purpose in setting standards for symbology but fall short in providing data to support the standards.

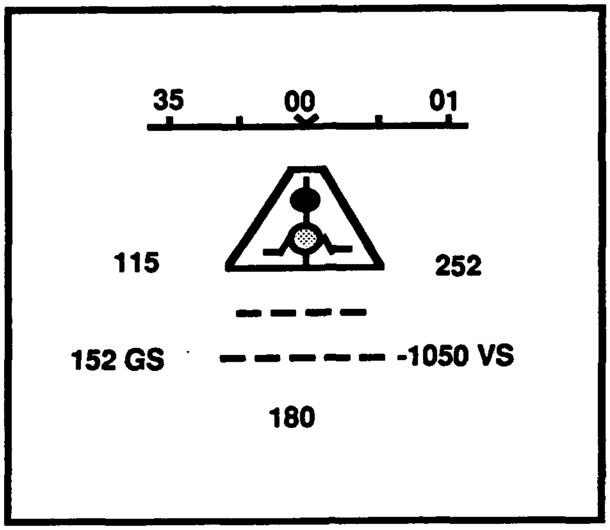

Figure 3. Example of a head-up display.

During the past 10 years, a great deal of research has been conducted on the effectiveness of HUDs. The impetus for some of this research has been the high incidence of pilots flying fully functional HUD-equipped aircraft into the ground (Haber, 1987). Much of the research has focused on object detection and avoidance, distance estimation, flight path control at low altitudes, and recognizing and recovering from unusual attitudes at high altitudes.

The following subsections describe the optical characteristics of the HUD, attentional and cognitive factors that affect performance with HUDs, and HUD design features important for spatial orientation. The subsections also address HUD symbology selection and format issues. The section concludes with a brief discussion of the need to design HUDs to be consistent with pilots' visual and cognitive capabilities. Detailed reviews of HUD research can be found in Egan and Goodson (1978) and Larish and Wickens (1991).

HUD Characteristics

A pilot's ability to use a HUD effectively is dependent on several characteristics of the HUD. Two characteristics that are relevant to the NVG-HMD system are the size of the HUD FOV and the collimation of the HUD symbology.

Field of view. The FOVs of HUDs are relatively small, ranging from about 12° to 18° (Brickner & Foyle, 1990). To see both the HUD symbology and the real world scene, a pilot's attention must be directed through the HUD's restricted FOV. Several research efforts studied the effect of FOV size on aircraft control and target detection.

The advantages of a wide FOV were reported in a series of three experiments (Venturino & Wells, 1990; Wells, Venturino, & Osgood, 1988, 1989). For example, Wells, Venturino, and Osgood (1989) investigated target detection and spatial awareness using helmets with FOVs ranging from 20° H x 20° V to 120° H x 60° V. Decreasing the size of the FOV significantly decreased the percentage of targets hit and significantly increased the time required to detect targets. The optimal FOV size depended on the task. Less difficult tasks could be performed effectively with a 20° H FOV while more difficult tasks required a 60° H FOV.

Brickner and Foyle (1990) investigated the effects of different size sensor FOVs (25°, 40°, and 55° H) on pilot performance. One experiment used a head-down display (HDD) and the other used a HUD. The HDD and the HUD formats differed only in their placement relative to the subject's line of sight. In both experiments, eight subjects flew a simulated helicopter through a slalom course. The display consisted of a takeoff site, course entrance and exits, horizontally striped pylons, and a ground grid. The subjects were instructed to take the most efficient path through the course and minimize the number of pylon hits and gate (opening between pylon) misses. Hits were defined as striking a pylon and misses were defined as missing a gate. The most efficient course was defined as one that minimized the average turn distance around the pylons.

Significantly fewer hits, misses, and smaller average turn distances were found with larger FOVs than with smaller FOVs. The researchers concluded that the subjects perceived the sensor display as the entire world rather than as a window into the world. That is, they did not keep objects in memory that had passed out of the field of view. Thus, narrow FOVs may increase memory demands for objects outside the FOV.

Display collimation. HUDs are collimated so the symbology, located physically about a meter from a pilot's eyes, is located at optical infinity. Hull, Gill, and Roscoe (1982) reported that accommodation to a real world scene was closer to infinity than accommodation to the same scene represented in a collimated color photograph. Iavecchia, Iavecchia, and Roscoe (1988) found that, when subjects viewed a distant scene directly and through a HUD, accommodation shifted inward significantly (about +1 diopter) under the HUD viewing condition. Iavecchia et al. suggested that pilots perceive real world objects as more distant than they actually are when shifts in accommodation are brought about by viewing HUD symbology. Roscoe (1987a, 1987b) suggested that pilots cannot process HUD information and the real world scene simultaneously because the HUD symbology causes overaccommodation.

The results of Hull et al. (1982) and Iavecchia et al. (1988) suggest that either visual or cognitive depth cues cause overaccommodation when viewing HUD symbology. Norman and Ehrlich (1986) proposed that accommodation may be affected by the awareness that the HUD is physically nearby. Pilots know that they do not monitor symbols or characters at distances beyond arm's reach, certainly not as far as real world features.

Debate continues over the operational significance of pilot overaccommodation (Hale, 1990). Roscoe (1987a, 1987b) suggests that overaccommodation causes accidents. Other researchers (e.g., Newman, 1987; Weintraub, 1987) do not judge the problem to be as serious as Roscoe does.

Attentional Issues

Pilots often fixate on HUD symbology and ignore critical information in the real world scene (Brickner, 1989b; Fischer, Haines, & Price, 1980; Larish & Wickens, 1991). Thus, the effects of attentional switching on pilots' performance with HUDs (e.g., Fischer, 1979) must be considered as a potentially significant safety issue in adding symbology to NVGs.

Parallel versus serial processing. One objective of placing HUD symbology at the same focal distance as the real world scene is to facilitate parallel processing. However, the intrinsically different nature of the information presented on the HUD may contribute to the tendency for pilots to perceive the HUD as separate information (Fischer, 1979) and thus disrupt parallel processing.

When symbology is superimposed on the real world scene, a complex display is created whose movement differs from the real world scene alone (Larish & Wickens, 1991). As the real world scene moves across the visual field, the HUD symbology remains in the same location and is detached from the landscape. This enhances the perception that the pilot is looking through the display. Thus, pilots may have difficulty attending to the HUD and the real world scene simultaneously because they are perceived as different sources of information.

The results of several experiments (e.g., Brickner, 1989a; Fischer et al., 1980; Foyle, Sanford, & McCann, 1991; Larish & Wickens, 1991; Neisser & Becklen, 1975; Weintraub, Haines, & Randle, 1985) support the contention that HUD symbology and the real world scene may not be processed in parallel. Neisser and Becklen (1975) had student subjects watch a video display that superimposed two unrelated activities (i.e., bounce-passing a basketball and clapping hands). When one of the activities was defined as more important, the subjects failed to notice unusual events in the less important activity. A difference in the nature of two visual sources may be enough to interfere with parallel processing even though the sources are located in the same focal plane.

Fischer et al. (1980) used a simulation of a fixed wing aircraft's approach to a runway to examine pilot performance with a HUD. Eight experienced pilots each made an approach in a full scale Boeing 727 simulator with and without a HUD. Long reaction times and failure to detect an unexpected airplane on the runway suggested that the pilots had difficulty processing the HUD and external scene in parallel. Several pilots reported that they fixated on the HUD symbology to the exclusion of the external scene.

Weintraub et al. (1985) measured the time required for eight subjects to shift attention from symbolic displays to a collimated slide of a runway. Five of the subjects were pilots. One display was a collimated HUD and another was an HDD located 10° below the subject's line of sight at an optical distance of 3 ft. The HUD-to-runway reaction time was 86 milliseconds (ms) shorter than the HDD-to-runway reaction time. The researchers considered this difference to be functionally insignificant; however, three of the pilots failed to notice an unexpected stationary aircraft on the runway.

In both the Fischer et al. (1980) and the Weintraub et al. (1985) experiments, at least half of the pilot subjects (2 of 4 in Fischer et al. and 3 of 5 in Weintraub et al.) did not notice an aircraft on the runway. Fischer et al. suggested there is a tendency for serial processing to occur and for the pilots to attend more to the symbology than to the outside scene because "there is much more immediately perceivable change going on, calling for more attention" (p. 17). Despite degraded obstacle detection with the HUD in both experiments, the pilots preferred to fly with HUD and believed that it improved their performance.

Brickner (1989a) presented subjects with a dynamic simulation of a helicopter flight through a slalom course containing ground texture cues. The subjects were instructed to maintain a specific altitude while reducing pylon hits and gate misses. Brickner found that providing the subjects with altitude information on a HUD and not in the visual scene decreased altitude errors but significantly increased both pylon hits and gate misses. He interpreted his findings as demonstrating that, even though the HUD and the external scene were at the same physical and focal distance, they competed for the subject's attention and could not be processed in parallel. He suggested that the HUD produced a figure-ground relationship between the symbology and the simulated external scene that degraded time-sharing ability.

In a follow-on to Brickner's (1989a) experiment, Foyle et al. (1991) used a similar dynamic helicopter flight simulation to examine the effects of providing pictorial altitude information in the visual scene. The display allowed the subjects to estimate altitude directly from the visual scene cues (e.g., relative height of buildings) instead of having to read a digital HUD. Subjects maintained comparable altitude control in both the HUD condition and the pictorial display condition. However, when the subjects used only the HUD for altitude information, they made greater flight path errors than when they used the pictorial display. Foyle et al. argued that the information in the HUD and the synthetic external scene is perceptually segregated and requires serial processing. In comparison, the integration of the information available from the HUD into the external scene allowed the pilot to process the altitude and flight path information in parallel.

Attentional fixation and cognitive capture. Attentional fixation and cognitive capture are terms that have been used more or less interchangeably in the literature. Attentional fixation occurs when an observer attends to a specific element or area in the visual field for an inappropriately long time instead of scanning the entire field. The area may be a confusing or critical element in the external visual scene or a changing indicator in the symbology.

In many circumstances, there may be good reason for fixating longer than normal on one particular element in the visual scene. However, pilots may not realize how long they have focused attention on one item and may not notice other critical events in the visual field. As Brickner (1989b) noted, "The danger is that the pilot might 'forget' to look at the world and spend most of the time watching flight symbology, thereby ignoring obstacles and other crucial information" (p. 19).

Larish and Wickens (1991) investigated attentional fixation by presenting expected and unexpected events on the HUD and in a synthetic visual scene. The researchers used 20 instrument-rated pilots in a dynamic computer simulation of an approach to a landing. Task workload was manipulated by using two different levels of turbulence.

The pilots' reaction times to unexpected events presented on the display (a wind-shear warning) and in the synthetic visual scene (another aircraft on the runway) were slower when using a HUD than when using an HDD, especially during periods of high task workload. Larish and Wickens (1991) found no practical performance advantage for the HUD over the HDD. They concluded that the advantages of the conventional HUD may be related to its information content and collimation rather than to its physical location. These results were similar to those of Weintraub, Haines, & Randle (1984) and Weintraub et al. (1985).

Allocation of attentional resources. Wickens (1984) has proposed a multiple-resource theory of attention and time-sharing that is useful for explaining many of the findings discussed above. The theory states there are different attentional resources with unique properties rather than one pool of limited resources. Tasks that share resources are more likely to interfere with each other. Three dichotomous dimensions are used to define the resources: (a) two stage-defined processing resources (early vs. late processing), (b) two modality-defined encoding resources (auditory vs. visual encoding), and (c) two processing code resources (spatial vs. verbal). When two tasks demand common resources on any of the three dimensions, they are likely to interfere with each other. This may take the form of less efficient time-sharing, decreased performance as task difficulty increases, or decreased performance on one task as resources are directed to the other task.

Thus, Wickens' theory can explain the failure of pilots to process the external scene and the HUD symbology in parallel. Both tasks involve early processes (perceptual and central processing) rather than late processes (selection and execution of responses) and involve the visual modality. However, some symbols (e.g., vertical altitude tape) require spatial processing, while others (e.g., digital airspeed) require verbal processing. In comparison, the visual scene primarily requires spatial processing. According to Wickens' (1984) theory, the requirement to monitor the HUD and the external scene simultaneously should result in a degradation in information processing capability. The degradation is especially likely when the task requires a high level of workload.

Effects of practice. In the experiments discused above, the time that subjects practiced dividing attention between superimposed images was relatively small, ranging from a few minutes (Neisser & Becklen, 1975) to 2 hours (Fischer et al., 1980). However, these experiments did not report data on performance at the beginning or end of the practice trials or following different amounts of practice.

In a follow-on to the Neisser and Becklen (1975) experiment, Becklen and Cervone (1983) examined the effects of practice on subjects' ability to divide attention between two superimposed visual scenes. Increasing the subjects' practice from 30 to 60 s significantly increased the percentage of subjects who noticed unexpected events in the visual scene. Stoffregen and Becklen (1989) found that subjects noticed significantly more events in two superimposed visual tasks after 2 days of practice.

Wickens (1984) reviewed several experiments studying the effects of practice on time-sharing skills. He concluded that efficient time-sharing performance results from the combination of both automated processing of component tasks and a true time-sharing skill. The time-sharing skill involves developing optimal display sampling and response selection strategies and learning to integrate the information from different tasks. However, the extent that a time-sharing skill acquired in one environment can transfer to other environments is not well understood.

The research suggests that a pilot's ability to divide attention between HUD symbology and the external scene improves with practice. Newman (1987) proposed that a lack of experience using HUDs and HMDs was the major obstacle to their effective use. Therefore, the effect of practice on a pilot's ability to use the NVG-HMD effectively is an important issue that should be further investigated.

Spatial Disorientation

When external visual cues are degraded, such as in limited visibility, pilots get pitch and roll information from the aircraft attitude indicator to maintain correct spatial orientation. Therefore, an unambiguous display of pitch and roll attitude information is important when an aircraft is in an unusual attitude. Unusual attitudes can result from factors such as turbulence or distraction of attention. The HUD displays attitude information to keep pilots properly oriented while they look outside the aircraft and to help them recover safely from an unusual attitude.

Research cited in Deaton, Barnes, Kern, and Wright (1990) indicated that 30% of pilots flying with conventional HUD systems reported an increase in spatial disorientation when they used HUDs. Concern about HUD attitude displays has increased interest in improving the communication of attitude information and unusual attitude recognition in high performance fixed wing aircraft (e.g., Deaton et al., 1990; Dudfield, 1991; Ercoline, Gillingham, Greene, & Previc, 1989; Osgood & Venturino, 1990; Weinstein & Ercoline, 1991; Zenyuh, Reising, McClain, Barbato, & Hartsock, 1987). The researchers used simulated HUDs and low fidelity static and dynamic simulations to investigate the effects of different variables on reaction time and control error.

Several HUD design features have been identified that improve a pilot's spatial orientation and facilitate the recognition of unusual attitudes. Examples of the features are directional arrows, color coding, and angled pitch ladder lines. Although recovery from attitudes such as inverted flight may not be a serious problem for helicopter pilots, the design of the HUD attitude indicator display is important. Simmons, Lees, and Kimball (1978) observed that attitude information accounted for 35 - 45% of the information that a helicopter pilot needs during instrument flight.

Physiological Basis for HUD Design

The research suggests that pilots process information from the HUD and the external visual scene in a serial rather than a parallel manner. Previc (1989) suggested that attentional resources may be used more efficiently and some amount of parallel processing may be possible if engineers designed HUD symbology to be consistent with the natural perceptual capabilities of the visual system. He recommended that HUDs should (a) be consistent with the division of attention between near and far space, (b) exploit the global perceptual capabilities of the visual system that require fewer attentional resources, (c) use symbology cues that are important in elementary figure-ground separation and that are preattentive (i.e., before the commitment of attentional resources), and (d) apply a clear and unambiguous frame of reference for depicting the movement of the aircraft with respect to the horizon.

Previc (1989) suggested that the HUD information should be arranged in quadrants, with airspeed and altitude information located in the upper left and upper right quadrants, navigation and weapons information located in the lower left and lower right quadrants, heading information located in the lower center, and attitude information located in the middle of the display. All the information in each quadrant should be related to the same function to allow it to be processed during a single glance. Finally, he suggested that the upper right half of the visual field is better for processing information about distant objects, while the lower left half of the visual field is better for processing information about near objects.

Helmet-Mounted Displays

HMDs have some of the same properties as HUDs and much of the research discussed in the section on HUDs is relevant to HMDs. Although many of the results from HUD research may generalize to HMDs, there are at least three notable differences between HUDs and HMDs that need to be taken into account.

First, HMDs are located a few centimeters from the pilot's eyes, whereas HUDs are located about a meter away. Second, because HMDs attach to the helmet and follow the pilot's head, they are always in the pilot's FOV. Third, the pilot views HUD symbology and the real world scene binocularly; the HMD can display several combinations of monocular or binocular symbology and imagery. These differences add a level of complexity to HMD research that is not present in HUD research.

The remainder of this section is organized into five subsections. The first subsection discusses several issues in visual perception that are important for understanding pilot performance with HMDs. Issues in divided attention and spatial disorientation are briefly addressed in the second and third subsections. The fourth subsection describes the basic characteristics of the NVG-HMD system. The final subsection discusses three evaluations of prototype NVG-HMD systems.

Perceptual Aspects of HMDs

Four aspects of visual perception that are important for an understanding of aviator performance with HMDs are accommodation and convergence, binocular rivalry, distance estimation, and FOV. These are addressed briefly in the following paragraphs.

Accommodation and convergence. How the eye responds to HMD symbology and imagery is of critical concern to the design of the HMD. Four HMD configurations are likely: binocular imagery and symbology, monocular symbology and imagery presented to different eyes, monocular symbology and imagery presented to the same eye (e.g., the AH-64A Helmet Display Unit), and binocular imagery and monocular symbology (e.g., the NVG-HMD).

McLean and Smith (1987) reviewed research on the effects of monocular and binocular viewing of HMD imagery and symbology. They concluded there was evidence that night vision device imagery should be binocular but that additional research was needed to determine whether symbology should be monocular or binocular.

Moffitt (1989) examined convergence and accommodation to different HMD configurations with varying scene backgrounds and attentional instructions. Two subjects viewed a collimated slide of symbology superimposed on collimated slides of either clouds or mountains. The subjects were required to attend first to the symbology and then to shift their attention from the symbology to the external scene. Viewing monocular symbology (one eye was blocked or occluded[4]) produced less accurate convergence and accommodation than viewing binocular symbology. Viewing the scenery decreased the effect.

Binocular rivalry. Binocular rivalry may occur when a display presents different stimuli to each eye. For example, the AH-64A Helmet Display Unit displays Forward Looking Infrared (FLIR) imagery and symbology only to the pilot's right eye. It may also occur when symbology is presented on one of the two tubes of the NVG system, as is planned for the NVG-HMD system.

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[4]This occurs when a pilot viewing monocular imagery and symbology eliminates binocular rivalry by closing the other eye (e.g., the AH-64 Helmet Display Unit).

Little research has been devoted to studying pilots' ability to control attention during tasks involving dichoptic viewing (i.e., substantially different input to each eye). Neisser and Becklen (1975) found that subjects were less accurate at getting information from two scenes when the scenes were presented to separate eyes than when the scenes were presented to both eyes. Kimchi, Rubin, Gopher, and Raij (1989) found that simple target detection was equivalent under dichoptic and binocular viewing. However, in a follow-on experiment, Gopher, Grunwald, Straucher, and Kimchi (1990) found performance decreased on tracking and letter classification tasks under dichoptic viewing conditions.

Brickner (1989b) proposed that the binocular rivalry created when symbology is superimposed on the NVG image of only one eye creates two potential problems. First, if the symbology presentation in front of the intensifier tube is too bright, the NVG's automatic gain control changes the gain on the intensifier tube, producing different display brightnesses and different levels of dark adaptation in the two eyes. The resulting brightness difference is known to cause illusions of motion in depth. Second, the differences in the images may interfere with their fusion. One of the images may be suppressed (possibly without the pilot's awareness), resulting in a loss of contrast sensitivity and a decrease in the signal to noise ratio.

Distance estimation. As is the case with HUDs, pilots frequently report that objects appear farther away when viewed through an HMD. For example, 65% of the AH-64A pilots surveyed by Hale and Piccione (1990) reported this effect when viewing FLIR imagery through the AH-64's Helmet Display Unit. However, none of the pilots reported experiencing the problem when looking through the symbology at the real world.

In comparison, Bennett and Hart (1987) found that objects appeared closer to AH-64A pilots when viewed through a FLIR than with the unaided eye, especially when the FLIR imagery was bright. This contradicts the results of Roscoe (1984), Iavecchia et al. (1988), and Hale and Piccione (1990).

The extent that the superimposed symbology of an HMD may contribute to the misperception of distance reported with HMDs used with night vision devices like NVGs and FLIR sensors is unclear. It is likely that the sharp-edged, high brightness symbology elements will have some effect on NVG image perceptions. NVGs and FLIRs alone are generally considered to cause distances to be overestimated. The limited data of Foyle and Kaiser (1991), however, indicate substantial individual differences in perceptual accuracy (both overestimation and underestimation of distance) for both direct vision and viewing through NVGs and FLIRs.

Because of the proximity of the HMD display and the pilot's eye, it is unlikely that the HMD display provides an effective stimulus for overaccommodation. Therefore, if overaccommodation is occurring, it must be caused by other factors. Most likely, poor distance estimation results from a complex interaction of factors such as image and symbology size and brightness, symbology location, FOV, and monocular and binocular presentation modes.

Field of view. The effects of FOV size on pilot performance discussed previously indicated that aircraft control and obstacle avoidance performance improved with larger FOVs. If magnification is used with a consequent smaller FOV, however, detection and identification for objects in the FOV will be improved (i.e., they will be seen farther away), while the probability of detection and identification will be reduced due to objects being beyond the FOV. These findings can probably be generalized to HMDs. However, when determining the potential benefit of larger FOVs for HMDs, the resulting increase in helmet weight must be considered.

Pilots fly most fixed wing aircraft at considerably higher altitudes and faster airspeeds than rotary wing aircraft. The high gravitational forces involved in maneuvering and ejecting can harm pilots wearing helmets weighing more than 3.5 lb (Tatro & Taylor, 1989). Therefore, the HMD FOV in fixed wing aircraft is kept small to reduce weight. Furthermore, because fixed wing aircraft are flown at higher altitudes than rotary wing aircraft, the size of the HMD FOV may not be as critical. For example, some experiments involving fixed wing aircraft showed satisfactory pilot performance with FOVs as small as 12° (Arbak, 1989).

Rotary wing pilots also experience high gravitational forces during certain tactical maneuvers. However, rotary wing pilots need a wide FOV to detect and avoid obstacles in different directions during missions flown at low altitudes (Simmons et al., 1985). Research is needed to determine the optimal tradeoff between FOV size and factors such as resolution and helmet weight for rotary wing pilots.

Divided Attention

Most of the research on the effects of superimposed symbology on aviators' attention has been performed with HUDs and was summarized in the preceding section. Aviators also find it difficult to attend simultaneously to collimated HMD symbology and either real world scenes or collimated imagery (Crowley, 1991; Hale, 1990). However, because of several characteristics unique to HMDs (e.g., the proximity of the HMD image and symbology, monocular vs. binocular imagery and symbology, slaving of imagery and symbology to head movement), attentional effects are difficult to separate from perceptual effects. Whatever the cause, pilots logically must lose some amount of time switching attention between the imagery and symbology when using HMDs.

As discussed before, helicopter pilots wearing NVGs must use systematic scanning patterns to compensate for the limited NVG FOV. Effective scanning techniques are acquired through training and experience and may be resistant to change. Superimposing symbology on the NVG image may interfere with previously acquired scanning patterns. Therefore, this problem warrants investigation.

Spatial Disorientation

Because the HMD is attached to the head, spatial disorientation is likely to occur when a pilot looks in a different direction than the one in which the aircraft is moving; this is known as off-axis viewing. Another factor that may contribute to spatial disorientation is that the attitude indicator is referenced to the airframe rather than to the pilot's gaze. The frequency of pilot spatial disorientation increases with a narrow FOV, as with the AH-64A Helmet Display Unit and the NVG-HMD, because the narrow FOV eliminates many peripheral cues that allow the pilot to resolve the sensory conflict (Hart & Brickner, 1989).

NVG-HMD Characteristics

HMD symbology for the NVG is created by taking data from onboard aircraft systems, converting any analog signals to a digital format, generating the symbology, and projecting the symbology from a miniature cathode ray tube (CRT) onto a semitransparent combiner lens. Depending on the design approach, the combiner lens is mounted either in front of or behind one of the NVG intensifier tubes. The pilot sees what appears to be a single image with superimposed symbology.

Figure 4 shows the visual images provided the two eyes by the NVG-HMD. The NVG-HMD image is a combination overlay of the visual perspective and symbology. Actual symbology in the typical NVG-HMD will appear brighter rather than darker, as depicted in Figure 4. The NVG-HMD allows pilots to select different symbol sets during different phases of flight (e.g., hovering, cruise) and to display separate symbol sets to the pilot and copilot.

The NVG-HMD symbology must have enough brightness and color contrast to be distinguished from the NVG external scene image. Both the pilot and the copilot can independently adjust the brightness of the NVG-HMD symbology or turn off the symbology .

If the combiner lens is positioned in front of the photocathode, the symbology will be the same monochromatic green color as the NVG image. In this configuration, the brightness of the symbology can cause the brightness of the

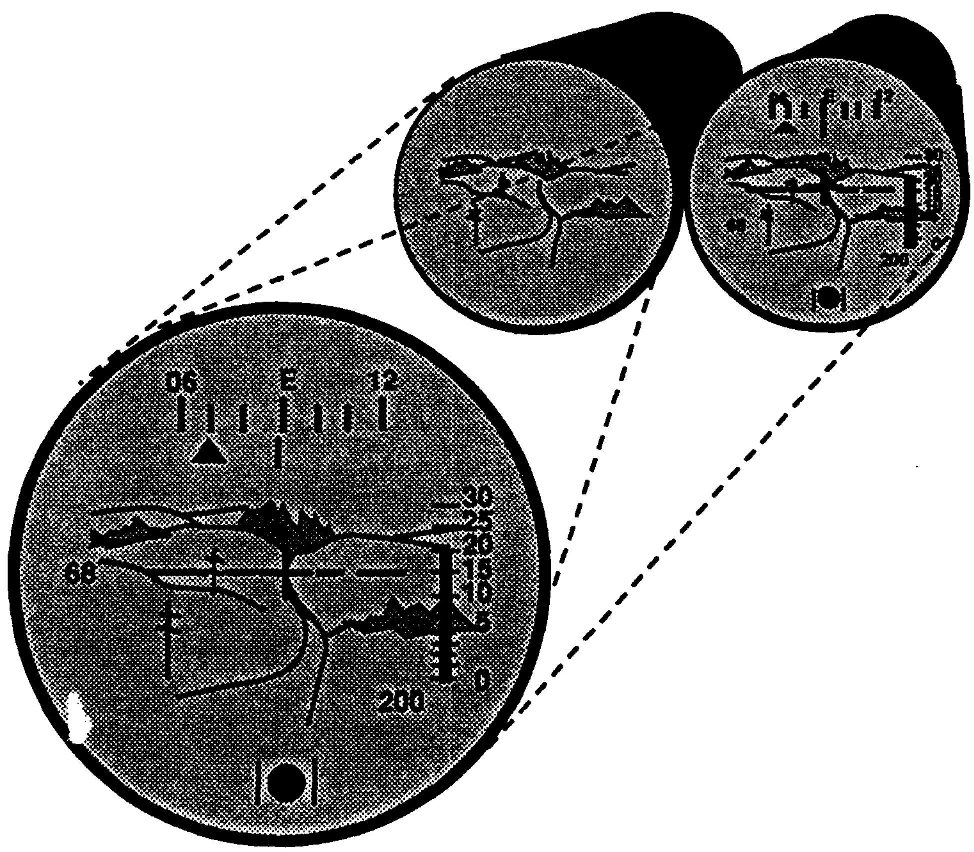

Figure 4. NVG-HMD visual perspective.

NVG image to decrease. In doing so, the goggle reduces its sensitivity, resulting in a dark image and reduced quality of the external scene view (Brickner, 1989b). Under these conditions, objects in the external scene will have less contrast and be more difficult to detect.

In comparison, if the combiner lens is positioned in back of the photocathode, the brightness and color of the symbology are independent of the NVG display. In this case, the brightness of the NVG image does not affect the brightness of the symbology and the symbology remains if an NVG intensifier tube fails.

Both the NVG external scene image and the symbology are collimated CRT images. Both images have the same focal distance and theoretically require the same amount of accommodation. Thus, there should be no response time delays attributable to reaccommodation when the aviator switches attention between the symbology and the external scene.

As discussed previously, McLean and Smith (1987), Moffitt (1989), and Brickner (1989b) noted that pilots perceive HMD symbology as being closer to their eyes than the external scene image. This may occur with NVG-HMDs even though both the external scene image and the symbology are projected at the same focal distance and are seen through the same optical system. Presently, the accommodation of a pilot wearing an NVG-HMD cannot be measured; therefore, it is difficult to determine if differences in accommodation occur.

Evaluations of Prototype NVG-HMD Systems

Except for the AH-64A Helmet Display Unit, little empirical research has been reported on pilot performance using operational HMD systems in rotary wing aircraft. The U.S. Army, the U.S. Air Force, and the U.S. Marines reported informal evaluations of prototype NVG-HMD systems in rotary wing aircraft. The following paragraphs describe the results of the evaluations.

U.S. Army. The U.S. Army developed and informally evaluated a prototype NVG-HMD for rotary wing aircraft known as the micro-HUD (Simmons et al., 1985). Ten helicopter pilots wore the micro-HUD during flights in the UH-1 aircraft. The micro-HUD presented a different set of symbols to each eye by using small mirrors to reflect the information directly to the retina. Both the symbol generators and the mirrors were mounted on a pair of safety glasses worn between the aviator's eyes and the NVGs. Digital information representing altitude, trim, airspeed, and heading was presented to the left eye at the 3, 6, 9, and 12 o'clock positions respectively. A fixed aircraft position reticle and a moving horizon line were presented to the right eye in the center of the visual field.

The micro-HUD produced very poor quality symbology. Vibrations from the helicopter or slight movements of the glasses often caused the symbols to disappear. The brightness of the symbology was barely enough to be seen against the NVG image. Also, the pilots had difficulty monitoring the NVG external scene and the numeric symbols simultaneously or viewing two symbols at the same time.

Simmons et al. (1985) did not report performance data on the effectiveness of the NVG micro-HUD. Subjective evaluations by the pilots suggested that the micro-HUD provided sufficient information for helicopter pilots to fly a ground controlled approach with the NVG system turned off. In addition, the pilots generally considered the micro-HUD to be a labor saving device during instrument-dependent maneuvers. Therefore, the researchers considered the micro-HUD to be useful.

The researchers suggested improving the micro-HUD design by attaching the combiner lens directly to the NVG and changing the image generator to stabilize the symbology. These changes were apparently incorporated in more recent NVG-HMD prototype systems. Since the development of the early prototype NVG-HMD tested by Simmons et al. (1985), the design of the NVG-HMD device and the quality of the symbology have been significantly improved.

U.S. Air Force. Runyon (1985) described the results of a U.S. Air Force test of the feasibility of using an NVG-HMD system in helicopter special operations and for combat rescue missions. The NVG-HMD used an eyepiece attached to the end of one of the NVG intensifier tubes. A fiber optic cable connected to a CRT enclosed in an electronics box transmitted flight and navigation symbology to the NVG intensifier tube. Thirteen pilots subjectively evaluated the NVG-HMD during several mission segments.

Runyon (1985) cited the following conclusions from the test results.

- Using the NVG-HMD was feasible for all phases of special operations and combat rescue missions; it reduced pilot workload and made night operations safer.

- Using the NVG-HMD significantly reduced the need for intercom call-outs (e.g., altitude and airspeed) from other crewmembers.

- Most of the pilots preferred to use the vertical altitude tape instead of the vertical velocity scale.

- The HMD decreased the visibility of the NVG image even when the HMD intensity level was just above the absolute minimum, especially when using the ANVIS (i.e., more sensitive) NVGs.

- Except at high HMD intensity levels, HMD symbology was difficult to read when superimposed on bright areas (lack of contrast).

- The center of the FOV was cluttered by symbology.

- The numbers on the HMD were too small to be read quickly.

- Disconnecting the fiber optic bundle from the NVG slowed egress.

- Some pilots experienced eyestrain when shifting their attention between the symbology and the NVG image.

- The pilots judged that 1 hour of ground training and two low-level flights were required to train previously NVG qualified pilots.

Runyon reported that the change from binocular to monocular vision may be the source for the eyestrain, preventing simultaneous viewing of the visual scene and the HMD symbology.

All 13 pilots judged that the NVG-HMD could reduce pilot workload and make night operations safer but that the NVG-HMD did not expand night flying capabilities. As a result of the test, the Air Force (a) moved the symbology from the center of the HMD to cover approximately two-thirds of the 40° NVG FOV, (b) increased the size of the numbers, and (c) placed a master caution light indicator on the HMD.

U.S. Marine Corps. More recently, the U.S. Marine Corps completed an evaluation of three prototype NVG-HMD systems using a variety of rotary wing aircraft (U.S. Marine Helicopter Squadron One, 1989). The NVG-HMD systems provided symbolic flight and navigation information. Eighty helicopter pilots representing the four armed services observed NVG-HUDs on demonstration flights. After the flights, the pilots completed a questionnaire describing the difficulties of using the NVG-HMD, the experiences of discomfort, the workload, and the potential of the NVG-HMD for enhancing mission performance.

Six highly experienced pilots used the NVG-HMD systems in more extensive evaluations during four terrain flight tasks under four levels of ambient light. The four tasks were (a) terrain flight over desert, (b) single and multiaircraft confined area landings in heavy woods, (c) shipboard landings, and (d) low level overwater operations. The ambient light levels ranged from a full moon and clear skies to no moon and overcast skies. The pilots performed the tasks once while wearing NVGs alone and again while wearing the NVG-HMDs.

The pilots used a variation of the Cooper-Harper scale (Cooper & Harper, 1969) to rate their workload during each task. Workload ratings were higher in all conditions when the NVG was used without the HMD, especially under low light conditions. However, no tests of statistical significance were reported.

The Marine Corps reached the following conclusions:

- The addition of the HMD to the NVG made flying considerably safer than flying with the NVG alone, primarily as a result of a reduction in crew workload.

- Using the NVG-HMD eliminated many of the inside/outside scan transitions otherwise required by pilots to access flight status information.

- The NVG-HMD is most useful when flying in environments that require the pilot's total attention to be outside the cockpit, such as terrain flight and ship landings.

- Using the NVG-HMD reduced the workload of the pilot not on the controls during terrain flight navigation and ship landings.

Perceptual and Attentional Issues

The literature on the NVGs, HUDs, and HMDs indicates that two issues stand out as most important for evaluating the effect of adding symbology to the NVGs: perceptual judgment errors and attentional switching. These issues have been discussed together in the sections on NVGs, HUDs, and HMDs. However, their importance for NVG-HMD research warrants that they be addressed separately in this section.

Perceptual Judgment Errors

In research that uses perceptual judgments through NVG-HMDs as criterion measures, it is important to understand the perceptual errors that characterize direct vision as well as vision through different types of imaging systems. For example, research by Gilinsky (1955) and Palmer, Mitchell, and Pettit (1979) indicated that judgments of equivalence in size and angular subtense of objects located at different distances varied significantly from the true state both with direct vision and through television imaging systems. Galanter and Galanter (1973) and Wright (1966) found that distance estimation in the field to or from aircraft with the unaided eye is typically inaccurate but that training may be able to improve perceptual accuracy. In addition, the results of their research suggest that the specific conditions of viewing influence bias and accuracy. Substantial errors in aviators' judgments of altitude with direct vision were reported by Armstrong et al. (1975) for Army aviators and by Ungs and Sangal (1990) for Coast Guard aviators.

The literature reviewed in this report suggests that common perceptual judgment errors with NVGs are overestimation of distance and underestimation of closure rates; however, there is considerable variability in the accuracy (e.g. Foyle & Kaiser, 1991). The effects of NVG-based vision without symbology on perceptual judgments are poorly understood at present, with only a few studies on a few types of perceptual judgments. The effects of symbology on perception through NVGs remain an issue on which objective performance data are completely lacking. Research on the effects of symbology on perceptual judgments through NVGs will require comparisons with the same types of judgments through NVGs without symbology, with direct vision, and with measures of the actual state.

The effects of NVG-HMD systems on the accuracy of perceptual judgments are an unknown factor in their safety. Symbology is added to NVGs in part for the purpose of compensating for their perceptual judgment limitations. Symbology also has the potential of adversely affecting perceptual judgments with the NVG image viewed through it. Assessing the effects of symbology on perceptual judgments with NVGs is difficult, however, because of the substantial errors and pilot variability in these judgments with both direct vision and with NVGs.

Attentional Switching

The ability of pilots to time share or switch attention among the image and symbolic cues of the NVG-HMDs is a critical factor in their safety and operational effectiveness. However, this ability is not well understood. The selective attention research reviewed by Posner (1982) provides much of the basis of understanding that does exist, but it is general. Specific consequences for NVG-HMDs are uncertain in many respects.

HUDs were designed originally on the presumption that a common image-symbology focus would provide simultaneous perception of both types of cues. The research reviewed in this report and in Morey and Simon (1991) increasingly casts doubt about the validity of this presumption and suggests that symbology and the real world scene may be processed in a parallel manner rather than in a serial manner. Furthermore, there is some evidence that totally exclusionary switching of attention between image and symbology may exist, in which critical image cues may remain completely undetected when attention is on symbology and vice versa (e.g., Fischer et al., 1980; Foyle, et al., 1991; Larish & Wickens, 1991; Weintraub et al., 1984; 1985).

Although switching attention between symbology and imagery may occur, an aviator's ability to divide attention between the two information sources is likely to improve with extensive practice. The effects of practice on subjects' ability to divide attention between two tasks has been demonstrated in laboratory research (e.g., Becklen & Cervone, 1983; Stoffregen & Becklen, 1989; Wickens, 1984) but has little support in operational settings. In addition, there is some evidence that increasing the conformal characteristics of symbology (i.e., making symbols analogous representations of their real world counterparts) may make it easier for pilots to process symbology and imagery in parallel (Larish & Wickens, 1991).

Conclusions

The results of the review of the literature on NVGs, HUDs, and HMDs indicate that many of the perceptual and attentional problems associated with using these devices, though documented, are not well understood. With relatively little research available on HMDs and NVG-HMDs, little is known about the perceptual and performance consequences of using these devices. The major conclusions that can be drawn from the literature review are discussed in the following paragraphs.

- NVGs provide helicopter pilots with enhanced visual capabilities compared to unaided night vision but are limited by low resolution and a narrow FOV. Critical flight information can be obtained from the aircraft's instruments by looking under or around the NVGs or from another crewmember. However, this may result in an increase in individual and crew workload.

- Pilots using NVGs experience certain types of perceptual errors: they tend to overestimate distances and underestimate closure rates, become spatially disoriented, and experience high levels of fatigue and workload. Thus, the performance capabilities and limitations of pilots using unaided vision and using NVGs alone should be examined before attempting to evaluate the effects of adding symbology. In addition, factors affecting pilot performance with NVGs may interact with factors affecting pilot performance with HUDs and HMDs.

- When pilots view the external scene through a collimated HUD, they tend to overaccommodate when viewing the symbology, even though the symbology and the external scene are at the same focal distance. The symbology appears to be closer than the real world scene. Pilots have difficulty attending to both the HUD symbology and the real world scene and must switch their attention between the two. This may be due to cognitive influences on depth perception or to a requirement to process information in a serial rather than a parallel manner. The ability to divide attention between two activities presented on the same display is likely to improve with practice.

- When viewing both HUD symbology and a real world scene or a synthetic image, there is a tendency to fixate on one source of information. Thus, pilots experience difficulty detecting unexpected events in the symbology or the external scene, especially when under stress or high levels of workload. The variables that affect attentional fixation or cognitive capture are not well understood and should be investigated. However, attentional and cognitive factors appear to be equal to or more important than sensory and perceptual factors.

- Many findings from HUD research may generalize to HMDs. The difficulty pilots have dividing attention between symbology and the external scene is an example. However, characteristics unique to the HMD (e.g., proximity to the pilot's eyes, slaving to the pilot's head, and the potential for monocular or binocular symbology and imagery) should be investigated.

- Superimposing symbology on the NVGs has the potential for decreasing pilot and crewmember workload and increasing the safety of NVG flight. Most of the problems reported in evaluations of prototype systems were attributed to improper fit, adjustment, or operation of the NVG-HMD system. Perceptual and attentional problems with the NVG-HMD were cited indirectly. This may be because few perceptual or attentional problems existed or because their effects were small relative to fit, adjustment, or operational problems.

Recommendations for Research

In the evaluations of prototype NVG-HMD systems, helicopter pilots preferred using the NVG-HMD system to using the NVGs alone and judged that the NVG-HMD reduced workload. However, the evaluations provided little data to evaluate the effectiveness of the NVG-HMD. Additional research is needed to evaluate the factors affecting pilot performance with the NVG-HMD and to identify individual differences in perceptual and attentional abilities. This section discusses the primary research issues and suggests a research approach for investigating the issues.

Research Issues

The review of NVG, HUD, and HMD literature suggests there are three issues that should be investigated in a program of NVG-HMD research.

- Will adding symbology to the NVG affect pilots' judgments of distance, altitude, and closure rates compared to using NVGs alone?

- Will adding symbology to the NVG distract attention from critical events in the external scene or inside the cockpit?

- Will adding HMD symbology decrease or increase pilots' spatial disorientation?

In addition, individual differences may play a role in each of these issues and in the selection of pilots for NVG-HMD missions. The research should also identify the effectiveness of training as a solution to these problems.

Independent Variables

The literature suggests that several independent variables may affect pilot performance using the NVG-HMD. The variables can be organized into four categories: NVG characteristics, HMD symbology characteristics, pilot characteristics, and task/environmental characteristics.

Research has indicated that the NVG variables listed in Table 2 are likely to interact with the HMD symbology, pilot, and environmental/task variables. However, these variables are established by NVG design, so they can only be manipulated when comparing different versions of the NVGs.

Some of the variables listed in Table 3 (e.g., size and brightness) may also be established by design specifications, but they can be manipulated for experimental purposes. As discussed previously, existing design specifications for symbology are based on expert opinion rather than empirical research. Therefore, all the variables identified in Table 3 should be considered in a program of research. However, priority should be given to variables that are not yet determined by design specifications.

The variables identified in Table 4 are important because they represent individual differences that may moderate how effectively pilots can use the NVG-HMD system. Some of these variables (e.g., flight and NVG experience) may be obtained from existing records but other variables (e.g., sensory or cognitive ability, subjective workload) will have to be measured before, after, or during an experimental session.

The variables identified in Table 5 represent influences external to the NVG-HMD system and the user that may affect its use. All these variables can occur over a large range of values. In initial experiments, the researcher should select representative and extreme values to determine the relationship between these variables and the performance

Table 2

Independent Variables for NVG-HMD Research: NVG Characteristics

Variable	Description
Resolution	The spatial modulation (contrast) per unit visual angle that can be seen with the NVGs
Lag	The temporal rate of change in contrast that can be seen with the NVGs
Field of view	The size of the maximum visual area that can be seen with the NVGs
Brightness	The amount of light emitted from the screen
Contrast	The ratio of the brightest and darkest area of the entire screen, or parts of it
Display color	The colors provided by the display

measures. Subsequent experiments can use intermediate values to refine the variable-performance relationships.

The variables, identified in Table 2 through Table 5, are not exhaustive and are provided to guide research. It is not possible to investigate the effects of all the variables in a program of research. Therefore, the authors' judgments of the relative importance of the variables are presented in Table 6. Variables rated as high should be given priority in a program of research.

Dependent Variables

Performance measures. The effects of the NVG-HMD system on pilot performance can be measured in several ways, depending on the research issue. Table 7 suggests performance measures for each of the three research issues

Table 3

Independent Variables for NVG-HMD Research: HMD Symbology Characteristics

Variable	Description
Size	The height and width of the characters and figures
Location	The placement of the symbology
Field of view	The area within the NVG image that is occupied by the symbology
Residual field of view	The area within the NVG FOV that lies interior to the symbology FOV, excluding centrally located symbology
Density	The number of symbols on the display at one time
Format	The digital or analog form of the symbology
Brightness	The intensity of the symbology
Contrast	The ratio of the symbology brightness and the NVG image brightness
Color	The wavelength of the symbology
Movement	The displacement of the symbols over time
Rate of change	The relative frequency of symbol change

identified in Table 6. With two exceptions, the variables in Table 7 are measures of time and accuracy of response. In addition to collecting time and accuracy measures, it is advisable to examine the manner in which pilots trade off time and accuracy in determining their response strategies.

Table 4

Independent Variables for NVG-HMD Research: Pilot Characteristics

Variable	Description
Sensory/perceptual	The detection, organization, and interpretation of visual information
Cognitive	Information processing and the allocation and division of attention
Eye dominance	The tendency for one eye to dominate visual perception
Flight experience	The amount and type of rotary wing experience
NVG experience	The amount and type of NVG experience
Training/practice	The amount and type of instruction to improve performance on the task
Fatigue	Extended performance and exposure to difficult environmental conditions
Subjective workload	The pilot's perception of task demands

Table 5

Independent Variables for NVG-HMD Research: Environmental/ Task Characteristics

Variable	Description
Ambient illumination	The amount of light available in the environment, whether from natural or cultural light sources
Scene content	The amount and type of detail in the external scene
Scene movement	The amount, type, and rate of object displacement in the external scene
Task workload	The mental and physical demands of the task

Table 6

Importance of Variables for NVG-HMD Research

Variable	Distance judgment	Event detection	Spatial orientation
	Research issue		
NVG characteristics			
Resolution	High	Medium	Medium
Field of view	High	Medium	High
Brightness	Medium	Medium	Medium
Contrast	High	Medium	Medium
Display color	Medium	Medium	Medium
HMD symbology characteristics			
Size	Medium	Medium	Medium
Location	Medium	High	High
Field of view	High	High	Medium
Residual field of view	High	High	High
Density	Medium	High	Medium
Format	Medium	High	Medium
Brightness	High	High	High
Contrast	Medium	High	Medium
Color	Medium	High	Medium
Movement	Medium	High	High
Rate of change	Medium	High	Medium
Pilot characteristics			
Sensory/perceptual	High	High	High
Cognitive	Medium	High	Medium
Eye dominance	High	High	Medium
Flight experience	Medium	Medium	Medium
NVG experience	High	High	High
Training/practice	High	High	High
Fatigue	High	High	High
Subjective workload	High	High	High
Environment/task characteristics			
Ambient illumination	High	High	High
Scene content	High	High	Medium
Scene movement	Medium	High	High
Task workload	High	High	High

Table 7

Dependent Variables for NVG-HMD Research

Research issue	Dependent variables
Distance judgment	Accuracy of distance judgments Accuracy of altitude judgments Accuracy of closure rate judgments Accommodation and convergence
Event detection	Time to detect critical scene events Time to detect critical symbology events Accuracy of recall of scene events Accuracy of recall of symbology events Accuracy of control movements Scanning patterns (eye movements)
Spatial orientation	Accuracy of recall of aircraft attitude Time to recognize unusual attitude Time to recover from unusual attitude Accuracy of control movements

Workload measures. One of the reported advantages of adding symbology to the NVG is that it reduces pilot workload. The effects of the NVG-HMD on pilot workload are not well understood and should be investigated. Therefore, research on the factors affecting pilot performance with the NVG-HMD should include measures of pilot workload.

Two types of workload measures are appropriate: subjective and physiological. Subjective workload measures commonly used in aviation research are the National Aeronautics and Space Administration Task Load Index (NASA-TLX) (Hart & Staveland, 1987), the modified Cooper-Harper Scale (Cooper & Harper, 1969), and the Subjective Workload Assessment Technique (SWAT) (Reid, Shingledecker, & Eggemeier, 1981). Heart rate variability has generally been found to be the most reliable physiological measure of workload (Hicks & Wierwille, 1979; Meister, 1985).

Research Apparatus

The effects of the variables identified in Table 2 through Table 5 can be examined using three types of research apparatuses: laboratory simulation devices, flight simulators, and operational aircraft. The following paragraphs discuss the characteristics, advantages, and disadvantages of each type of apparatus.

Laboratory simulation devices. Laboratory simulation devices are suitable for investigating attentional (event detection) problems with the NVG-HMD. Two general paradigms for studying divided attention in laboratory simulations are passive observer and active controller.

In the passive observer paradigm (e.g., Brickner & Staveland, 1989), the subject observes prerecorded video footage of helicopter flights from videodiscs or videotapes. The subject monitors and responds to critical events in the external scene (e.g., an aircraft crossing one's flight path) and in the symbology (e.g., airspeed going out of tolerance). This paradigm permits the researcher to study the subject's ability to divide attention between two visual tasks. Performance measures are reaction times to expected and unexpected external scene and symbology events. In addition, the researcher can study visual scanning patterns by recording eye movements with a head-mounted eye tracker. The principal advantages of the passive observer paradigm are control of the external scene and symbology events and the realism of the scene. The principal disadvantage is the subject's passive rather than active role.

Figure 5 illustrates an apparatus suggested by the work of Neisser and Becklen (1975) that can be used with the passive observer paradigm to simulate NVG-HMD viewing conditions (i.e., monochrome imagery presented to both eyes and superimposed symbology presented to the left or right eye). The device uses a videotape/videodisc player for generating the visual scenes and a personal computer for superimposing symbology and recording responses.

In the active controller paradigm (e.g., Brickner & Foyle, 1990), the subject controls critical parameters of a simulated aircraft such as airspeed and altitude while following a specified flight path. This paradigm permits the researcher to study the subject's ability to divide attention between a psychomotor control task and one or more visual search tasks. Generation of the dynamic visual scene, presentation of symbology, and recording of responses are performed by a graphics workstation computer. Performance

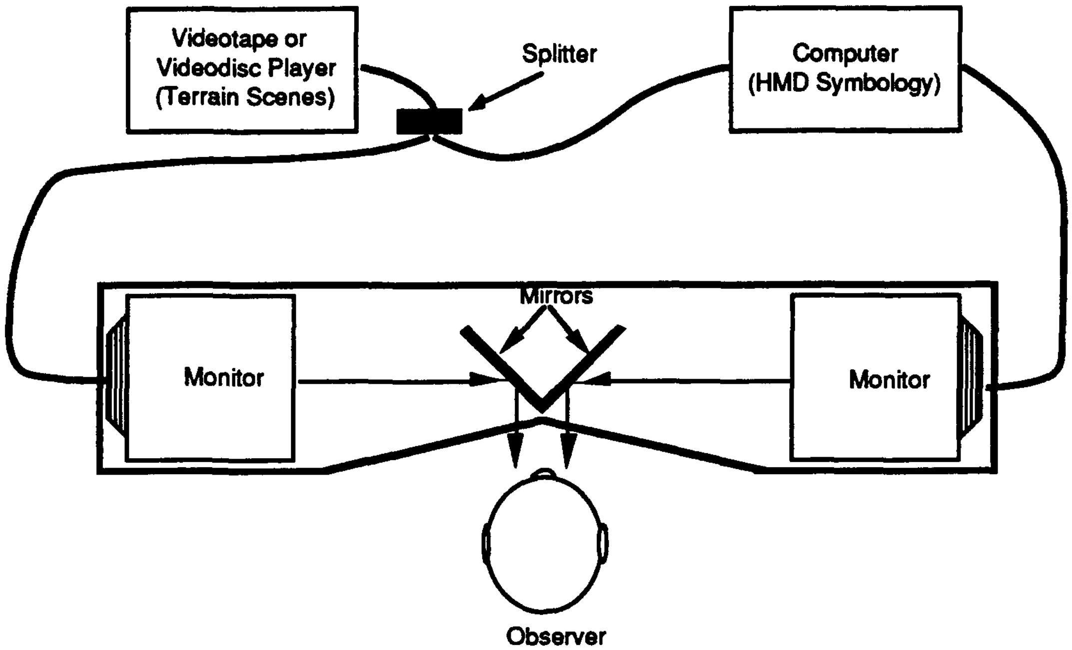

Figure 5. NVG-HMD laboratory simulation apparatus.

measures are flight path deviations and reaction times to expected and unexpected external scene and symbology events. As with the passive controller paradigm, the researcher can measure eye movements.

The principal advantage of this paradigm is the similarity of the task situation to the operational environment. The principal disadvantages are the lack of control over the external scene and symbology events and the relatively low realism of the visual imagery.

Flight simulator. A more realistic representation of the flight environment is provided by a flight simulator than in the laboratory simulation. A flight simulator also permits greater control in a safe environment over the conditions of the experiment and the variables under investigation than does an operational aircraft. The researcher can initiate and terminate maneuvers at any point and is able to study the pilot's behavior in either an active or passive role. A flight simulator is suitable for investigating attentional and spatial disorientation problems with the NVG-HMD.

Operational aircraft. The operational aircraft is the target environment of the NVG-HMD system and has the lowest degree of experimental control. The aircraft is most appropriate for studying the effects of adding symbology to the NVG on distance, altitude, and closure rate judgments. However, the flight tasks and the range of conditions under which pilot performance can be evaluated are limited by safety, operational considerations, and available terrain. The aircraft is better suited for observational than controlled research; therefore, it should be used to supplement laboratory and flight simulator devices in an NVG-HMD research program.

Research Approach

This subsection recommends a research program for investigating performance issues with the NVG-HMD coordinating the use of the three types of research apparatuses. Recommendations are made in Table 8 and are discussed in the following paragraphs for using each apparatus to investigate specific research issues. The recommendations reflect the availability of the required personnel and equipment, the cost of implementing the research approach, safety considerations, and the required level of realism.

Research should begin with a series of experiments to investigate the effects of the NVG-HMD on the pilot's ability to divide attention between external scene events and symbology events. The initial experiments should use the passive observer paradigm and a laboratory simulation device like the one illustrated in Figure 5. The independent variables should be (a) identified as important in the literature, (b) of practical significance to the Army, and (c) not already determined by design decisions. Two variables that clearly meet these criteria are amount of practice and eye dominance.

The research program should then be extended to examining problems in divided attention and spatial orientation with the NVG-HMD using a flight simulator. This research should concentrate on the pilot in the active controller role. A near-term goal of this research should be to investigate the effects of variables such as the amount of practice and symbol density that may have an impact on NVG-HMD training and operational use. A far-term goal should be to investigate the effects of variables such as symbology format and location for which design changes may be appropriate.

Table 8

Recommendations for Using Research Apparatuses in an NVG-HMD Research Program

Research apparatus	Research issue		
	Distance judgment	Event detection	Spatial orientation
Laboratory simulation		X	
Flight simulator		X	X
Aircraft	X		

Two flight simulators, the Training Research Simulator (TRS) and the Simulator Training Research Advanced Testbed for Aviation (STRATA), are scheduled to be available soon to ARIARDA and should be considered for this research. The TRS is a UH-1 instrument simulator equipped with a visual system that presents computer-generated imagery on front and side window CRTs. Symbology can be superimposed on the visual scene presented on the CRTs and eye movements can be measured by a head-mounted eye tracker. Unfortunately, the realism with which NVG conditions are simulated is limited and simulating viewing conditions specific to an HMD is not very realistic.

The STRATA is an advanced research simulator that integrates visual scene information and symbology on an HMD to create a virtual world for the pilot. The simulator has several features that make it attractive for NVG-HMD research, including advanced display and performance measurement capabilities. It can be programmed to simulate nighttime visibility conditions and can track pilots' head and eye movements. In addition, the STRATA can be used to investigate NVG-HMD monocular and binocular design issues such as eye dominance and binocular rivalry.

Laboratory simulation and flight simulators use two-dimensional collimated CRT displays. The displays do not provide an adequate representation of the pilot's visual world for investigating distance estimation problems with the NVG-HMD. Therefore, a portion of the research program should be devoted to investigating these problems using a combination of ground-based static displays and moving operational aircraft. For example, a pilot's ability to judge the distances of ground targets with the NVG-HMD could be assessed by placing the pilot in a tower overlooking a firing range that contains a variety of targets at known distances. However, a pilot's ability to judge closure rate with the NVG-HMD at realistic altitudes, which is the most critical aspect of distance estimation during low level helicopter flight, should be assessed using a moving operational aircraft.

Regardless of the apparatus used, the research program should evaluate the NVG-HMD for a variety of flight tasks. The tasks chosen should be ones in which the pilot needs aircraft status information while maintaining attention outside the aircraft. Examples of such tasks are terrain flight takeoff, terrain flight approach, hovering in- and out-of-ground effect, masking and unmasking, maneuvering in confined areas, and NOE flight. For instance, the NVG-HMD may be beneficial to pilots during a terrain flight approach to a confined area, but it may interfere with their ability to detect obstacles during NOE flight.

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