USAARL Report No. 2019-02

Recommended Army Aviation 40-501 Standards of Medical Fitness on Visual Acuity / Resolution With Respect to Degraded Visual Environment Flight Operations

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Warfighter Performance Group

February 2019

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
06-02-2019

2. REPORT TYPE
Final

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Recommended Army Aviation 40-501 Standards of Medical Fitness on Visual Acuity / Resolution With Respect to Degraded Visual Environment Flight Operations

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Lattimore, Morris R.
Harding, Thomas H.
Truong, James Q.

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Aeromedical Research Laboratory
P.O. Box 620577
Fort Rucker, AL 36362-0577

8. PERFORMING ORGANIZATION REPORT NUMBER
USAARL 2019-02

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Medical Research and Materiel Command
810 Schreider Street
Fort Detrick, MD 21702-5000

10. SPONSOR/MONITOR'S ACRONYM(S)
USAMRMC

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
N/A

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

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Standards identify specific visual performance expectations that can be minimally achieved under certain conditions. When considering a Degraded Visual Environment (DVE), an aviator's minimally-achievable acuity is a highly variable number. This is the result varied individual sensitivity responses to decremented contrast, and to decreased background luminance. Acuity responses under DVE conditions vary on a sliding performance scale as a function of those two influencing variables. Subjectively, the common attitude exists that decreased luminance and decremented contrast have the same magnitude or degree of adverse effect upon visual resolution. If that were a completely accurate contention, the goal of establishing why a modern DVE-based visual resolution standard is necessary would be a cleaner problem to address. Nevertheless, the goal is to establish a recommended visual performance standard such that an aviator is able to meet minimally achievable performance expectations under extremely challenging visual conditions.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
UNCLAS	UNCLAS	UNCLAS	SAR	37	Loraine St. Onge, PhD
					19b. TELEPHONE NUMBER *(Include area code)* 334-255-6906

REPORT DOCUMENTATION PAGE (SF298)
(Continuation Sheet)

14. Abstract (continued)

The current physical examination acuity standard does not make reference to the demands created by varied luminance and contrast effects that can represent DVE conditions. This recommendation of strengthened luminance- and contrast-testing parameters is intent on titrating individual visual performance variability with reference to DVE, such that DVE-based aviation fatalities can be eliminated through identification of those more likely to experience a DVE-based mishap. As this material is reviewed and analyzed, the objective performance requirements will become clearer, as will the recommended visual performance standard, resulting in a much reduced future fatality rate.

Table of Contents

List of Figures

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General Information

Introduction

The American National Standards Institute (ANSI) identify a standard as a document that provides requirements, specifications, guidelines, or characteristics that can be used consistently to ensure that materials, products, processes, and services are fit for their purpose. Army visual performance standards identify specific visual performance expectations for each major occupational skill set (e.g., Special Operations, Aviation, etc.). The vision standards are observable abilities under specific conditions, which explain the level of visual behavior to minimally be achieved during the successful performance of their specific assigned duties (e.g., luminance, resolution, contrast sensitivity, dark adaptation, stereopsis, color sensitivity). In other words, the purpose of a visual performance standard is to communicate expectations commensurate with one's minimal abilities to be routinely demonstrated. Standards which are too stringent likely will result in unnecessary elimination of qualified people, whereas standards which are too loose will likely result in poor job performance resulting in potential injury to military personnel. The establishment of operational-based vision standards for rotary wing pilots, as well as for other specialty skill Soldiers, is absolutely critical as a result of the complicated nature of their occupational duties, which compounds the difficulty in developing a specific visual resolution standard. Varied human physiological tolerance to performance-based stressors or obstacles is a fundamental issue common to every neurologic system. Consequently, human visual performance abilities are individually positioned along a sliding scale, subject to a variety of performance-based conditional determinants. There are logically both a number of known and unknown determinants (or controlling factors) that can complicate the establishment of a new or revised visual resolution performance standard. While some of these controlling factors are well-known, others are merely suggested, while others have not yet been verifiably identified.

Current Standard

The Snellen Acuity Standard for photopic visual performance is a scale that every Army Aviator and every Special Operations and Airborne Soldier today should be able to meet (if not naturally, then at least with a refractive correction). Most organic injuries leaving a lasting effect on the eye (i.e., a scar) are obvious disqualifiers; optical distortions preventing one from achieving a 20/20 acuity are also possible disqualifiers, depending on the nature of one's job description. When the initial visual performance standard was originally adopted by military aviation in the 1920s, any refractive error (or ametropic variance) was considered pathological, and therefore grounds for exclusion from flight training or flight duty. Today, refractive error is not considered to be pathological. Currently, anyone with a refractive error that's correctable to 20/20 visual acuity in each eye (via either laser surgery, contact lenses, or spectacles) is qualified to perform Army flight duties, unless there is an unrelated systemic health issue, or prior history of a loss of consciousness. Over the years a host of visual performance studies have separately evaluated the effects of varied luminance on acuity, as well as the effects of varied target contrast on visual performance. However, as illustrated recently in a review and meta-analysis (Lattimore, 2017), few investigators have assessed the systematic challenge of reduced contrast accompanied by decreased luminance. A great many refractive surgery patients began complaining of poor night vision beginning in approximately 2002, apparently due to several post-operative evaluations beginning to assess visual performance under varied luminance levels (occasionally accompanied by reduced levels of contrast) (Fan-Paul et al., 2002). This research effort has applied the critically- relevent studies on visual performance under the two primary conditional variables of reduced luminance combined with decremented contrast, and developed a recommended a visual performance standard for aviation and the specialty combat skills accession and retention.

Degraded Visual Environment

The operational flight-oriented visual deficiency phenomenon termed degraded visual environment (DVE) has seen at least a half-dozen proposed and developmental physical solutions seeking to aid duty performance while under DVE conditions. Despite the growing emphasis by the Army's Training and Doctrine Command (TRADOC) on the Human Dimension research program (The U.S. Army Human Dimension Concept, 2014), there are no previous U.S. Army Medical Research and Materiel Command (USAMRMC) research efforts oriented toward enhancing the natural ability of human unaided vision to perform at levels of sensitivity beyond expected ranges. The goal of this effort is merely to identify the normal variations in expected human sensitivity, and establish a cut-off point which would separate those capable of safely meeting the visual strains of modern aviation duty under DVE conditions, from those who could be better utilized elsewhere than aviation. This approach represents a departure from the engineering-based efforts at transmitting visual information electronically using a number of instrumented imagery technologies. The U.S. Army Aeromedical Research Laboratory (USAARL) does, however, have an ongoing customer funded program evaluating the effectiveness and utility of these proposed engineering-based imaging devices. These studies continue to bring in both research pilots and other seasoned operators as research subjects whose operational experiences are shared with USAARL staff. Based on first-hand experience with these emerging technologies, the existing medical vision standard review will continue, in addition to that of another investigator assessing the positive effects of macular pigment (lutein and zeaxanthin) optical density.

Few Scientific Manuscripts Contrast and Compare Visual Performance

The development of the recommended vision standards required for successful field operations within a DVE have been made with regard toward the key review / meta-analysis findings referred to earlier. There are very few scientific manuscripts contrasting and comparing visual performance under all the varied luminance conditions; some assess photopic and mesopic conditions, others assess mesopic and scotopic conditions, but only two have assessed all three luminance categories, and only one of them has factored in the compound effects of altered contrast and reduced luminance, acting on the visual perception of blur. Currently, aircrew medical vision standards have not been developed or even considered for meeting the current visual demands (i.e., DVE) that are placed on Army Aviators, even as the U.S. Army Research Develop and Engineering (USARDEC) community begins final development of emerging countermeasure technologies intended to master safe rotary wing flight under a DVE. A series of independent technological advances have had a major impact upon Army Aviation in general. Modern methods of providing visual information via electro-optics / visionics systems within head-mounted displays (HMDs) have extended the aviation operational envelope, but these devices were becoming increasingly incompatible with spectacle wear. Separate answers to that incompatibility had led to contact lens developments and refractive surgery solutions. Independently developed flat panel displays, backlit by white or colored Light Emitting Diodes (LEDs) have become an additional means of transferring visual information to pilots. However, the shorter blue wavelengths, and the near ultraviolet wavelengths inclusive within almost all LED outputs complicate the visual performance picture via their induction of alterations in photopigment chemical structure, along with associated alterations in neuro-ophthalmic metabolic activity. The shorter blue wavelengths are capable of altering rhodopsin's chemical structure (Noell, 1980), thereby adversely affecting dark adaptation and logically, adversely affecting mesopic visual performance. Associated demands are also placed upon our nation's military aviators, who now are further challenged by small print, varied lighting conditions, fatigue, accommodative inflexibility and the blurred vision stemming from fatigue. Last of all, the use (and possibly abuse) of the numerous over-the-counter nutritional supplements available to military personnel can cause poorly-determined, ill-defined compensatory physiologic challenges, as well.

Deployed Mishaps and Losses Under DVE

Operations in the Iraq and the Afghanistan theaters have highlighted flight operational activities within degraded visual environments as presenting a significant risk to safe rotary wing aircraft flight operations (NATO HFM-162; 2012). A DVE can be caused by partial or total loss of visibility from airborne dust, sand, or snow stirred up by the helicopter's rotor downwash. This condition has been termed brownout (or whiteout). DVE can also be caused by a combination of clouds, haze, and moonless / starless nights, and can potentially cause a loss of spatial orientation and situational awareness, which has on several occasions led to CFIT, accompanied by the loss of aircraft and/or personnel. More than a third of all helicopters lost in Iraq and Afghanistan have crashed because of CFIT while flying over the endless desert sands. In peacetime, while flying over water, CFIT has subsumed the majority of lives lost. Landing while under DVE conditions (which is defined as the combination of both low luminance and low contrast visual challenges) has created a major dollar cost to the Army in the last 15^{+} years of combat experience, while flying in Iraq and Afghanistan. Over an 8-year period of combat-based flight activities within Iraq and Afghanistan, Operational flights under DVE conditions have cost the Army numerous rated aviator lives, as well as over $1 billion in rotary-wing aircraft damage, resulting from approximately 800 Class A accidents during the time period 2002 – 2009 (a class A accident involves the possible loss of one or more lives, with aircraft destruction or damage exceeding $2 Million).

The potential fielding of a variety of technological solutions in response to the DVE threat is the Aviation Program Executive Officer's (PEO's) top priority. While these USARDEC-developed technological counter-measures to DVE have the goal of making landing, navigating, and actual fighting easier, the counter-measures themselves very likely exceed some individual's sensory limitations in ways that are not addressed under current physical examination standards. Eighty percent of rotary wing aircraft losses and 70% of aircrew fatalities during OIF / OEF were due to noncombat factors, including the presence of a DVE (CONOPS for Aircraft Operations in DVE, 4 April 2011, USAACE CRD). In the last decade, 103

Americans have been killed in Army helicopter crashes attributed to DVE conditions, most frequently brownout, at an associated loss of over billions of dollars. USAARL investigators have been involved in 5 major Research, Development, Test and Engineering (RDT&E) efforts, core-funded by USAMRMC, and extramurally-funded by a variety of Army engineering laboratories. One such study that was recently completed last summer is an engineering-based series of studies examining the usefulness of objective multi-sensory cueing strategies (Multi-Sensory Cueing Synergy Assessment… In Support of Flight Operations Within a Degraded Visual Environment – a draft report submitted for review on 17 July, 2016: authored by Deborah Russell, Keegan Statz, John Ramiccio, Mike Henderson, Ralph Salazar, David Still, Leonard Temme, SPC Will Weiser, SPC Heath COX, and Morris Lattimore). All such scientific investigative activities are focused on achieving a greater understanding of DVE, as well as determining the best means of mitigating these disastrous effects associated with attempting to conduct military aviation operations under these conditions.

Human Visual Performance Characterization

Human visual performance characterization is a goal published within the Training and Doctrine Command's (TRADOC's) Human Dimension White Paper, initially drafted in 2007 and republished in 2014 as a TRADOC Pamphlet. This current atypical analysis of visual resolution limits, as determined by two conditional variables, could be construed as a "high-risk/high payoff" topic. A review of these limits of human unaided visual resolution under conditions of DVE were initiated in hopes of spurring a more advanced research task area evaluating and modeling individual unaided DVE-based physiological and neurological demands and responses. The natural world's major visual performance challenge is in determining the way ahead when engulfed in a heavy fog, or within an extended sand storm (as is experienced in South west Asian desert climes. The "chamal" winds, illustrated by the five photographs at the end of this section, can prove to be extremely disorienting. Any attempt at ground mobility, either on foot or in a vehicle is met with extreme uncertainty as to finding a safe way ahead. Once on the move, stopping prior to finding a safe-haven shelter can be fatal. Any attempt at rotary wing flight under these conditions, as previously articulated, can also be fatal. When adding sunset and the advent of night-based activities, a sandstorm can remove almost all edge and border detection sensitivities, complicating the visual field to the extent that not even night vision goggles would be of any practical or useful benefit. The exponential increase of military aviators having received refractive surgery since the late 1990s has increased the number of subjectively-reported night vision disturbances, such as decreased contrast sensitivity. Standardized contrast sensitivity scales for normal persons within the mesopic range of luminance conditions, which is presumed to include Army aviation personnel, have not yet been definitively established. However, one only needs to understand the human basic sensitivity range in order to establish a safe cut-off point at which further candidates are excluded.

Figure 1. Example photographs of the “chamal” winds. Endemic to all of Asia, chamal winds are so strong that, when fully engaged, someone is literally unable to see a hand held in front of his or her face.

Review of Vision Testing Research

Visual Acuity Standards Development Review

August Colenbrander (in Duane’s Clinical Ophthalmology) reviewed the origins of the initial visual acuity standards and their developmental progress (Duane, 2005). Attempts at defining human visual resolution appears to have been initiated by Heinrich Kuchler in 1843. An initial means of selecting letter-based fonts was set by Eduard Jager von Jaxtthal in 1854. The Snellen System of recording visual acuity was developed in the 1862 as a discrete, step-wise means of recording visual performance capability using optotypes, defined as “standard vision” that subtended 5 minutes of arc. The term visual acuity was coined by Donders in 1864; the term stems from the Old French word “acuite,” which is closely related to the medieval Latin term “acuitas,” meaning sharpen. In the 1880s, Edmund Landolt introduced a broken ring optotype, ultimately known as the Landolt Ring or the Landolt ‘C’ (1871). Coincident to Landolt’s work, was the work of Helmholtz from the 1860s to 1880s, publishing an in-depth analysis of physiological optics in 1864. A 20/20-sized letter, based on the commonly-accepted ocular resolution capability of most individuals was previously determined to have an angular means of visual stimulation representing 5 minutes of arc. The letter selected as best representing that angular measurement was the letter E. The capital letter E has 5 horizontal components (3 black bars and 2 white intervening spaces), each identified as representative of 1 minute of arc, which was determined to be the smallest identifiable angular component of a visual target (or a letter) to be readily discernable by most individuals. Over the intervening years, alternative means of assessing visual performance using acuity tests of alternative design did not appear until the 1940s through present day. The Campbell-Robson Chart demonstrated the normative range of one's contrast sensitivity (Campbell & Robson, 1968). In 1976, Ian Bailey and Jan Lovie (then at the Kooyong Low Vision Service in Melbourne) published a new chart, featuring a novel layout with five letters on each row with spacing between letters and rows equal to the letter size, separate charts of varied letter contrast were also published. The logMAR notation (logarithm of the minimum angle of resolution) was introduced in the same paper. As the name implies it converts a geometric sequence of letter sizes to a linear scale. The logMAR value for 20/20 is the number 0; positive logMAR values indicate reduced vision, and negative logMAR values indicate vision better then 20/20. The logMAR notation has gained widespread use in psychophysical studies, for parametric statistical calculations, and for graphical presentation of the results of multi-center clinical studies. Rick Ferris et al. of the National Eye Institute chose the Bailey-Lovie layout, implemented with Sloan letters, to establish a standardized method of visual acuity measurement for the Early Treatment of Diabetic Retinopathy Study (ETDRS) (1982). Other visual performance assessments have applied the basic Campbell-Robson system by using 20/40 sized letters uniformly distributed on a chart with 5 letters per line. The top line of letters was of the darkest contrast, with each successive line downward reducing in contrast by 1 log unit until the 20/40 letters were no longer visible. This end-point represented the maximum contrast sensitivity that could be elicited in that specific subject.

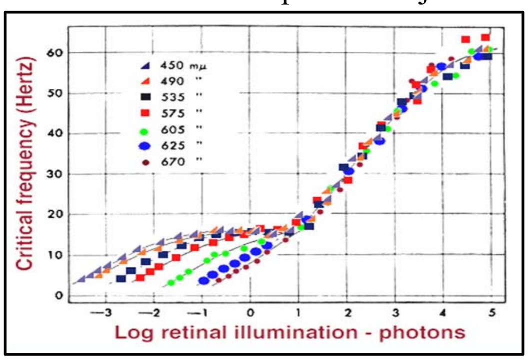

Figure 2. Critical Flicker Frequency (CFF) of a 19 degree test field over a range of retinal luminance (photon = troland) for different monochromatic lights of different wavelengths. Hecht and Shlaer's data from Hart Jr, W. M., The temporal responsiveness of vision. In: Moses, R. A. and Hart, W. M. (ed) Adler's Physiology of the eye, Clinical Application. St. Louis: The C. V. Mosby Company, 1987.

Visual acuity has been defined as the spatial-resolving capacity of the visual system, alternatively thought of as the capability to parse fine detail. There are various ways to measure and specify visual acuity, depending on the type of acuity task being considered; acuity limitations derive from diffractions and aberrations, as well as most importantly for this project illumination- and contrast-instituted limitations. The fundamental properties of light were considered by several of the early Greeks, Euclid and Archimedes to name two prominent individuals. Having studied mathematics under pupils of Plato, they apparently came to understand that light traveled in straight lines, as was able to be reflected off shiny surfaces (Heath, 1956). It was the early Greeks who probably used polished glass as magnifiers (Polyak, 1957). Spatial contrast computations are postreceptoral, requiring a neural computation that compares two positional luminance levels. Retinal horizontal cells, with their wide ranging dendritic trees are an essential element of the antagonistic center-surround organization to retinal bipolar cells and retinal ganglion cells (Kuffler, 1953). Cells are tuned to respond to specific spatial frequencies, under specific luminance and contrast levels (Kaplan, 2008). Schlear (in 1937), wrote an informative review of the relationship between visual acuity and degree or intensity of background illumination. The ability of the eye to distinguish detail is dependent, among other things, upon the intensity of the illumination falling upon the object. The measure of this ability is termed visual acuity and is expressed as the reciprocal of the angle (in minutes) subtended by the finest detail distinguishable. Therefore, the classical 20/20-sized letter "E" subtends a total of five minutes of arc; each horizontal line and each space between the three lines subtends one minute of arc.

Uhthoff (1886, 1890) first investigated the relation of visual acuity to illumination over an extensive range of intensities, and several years later Koenig (1897) reinvestigated it in so thorough a manner that his data have become classic. Since then numerous studies have demonstrated that at least three experimental variables that were not controlled in the earlier work can have a profound effect upon the results: pupil size was most the most important uncontrolled variable. The second most influential uncontrolled variable was the distance of the test object from the observer; and third uncontrolled variable the brightness and extent of the field surrounding the test object. All previously identified data have suffered as to their validity, since the natural, uncontrolled pupil was used in those experiments. Interestingly, brightness was discussed from two different reference points: internally, the retina is concerned with apparent brightness, as opposed to the external brightness of the visual field. Troland (1916) proposed the photon as a unit of retinal brightness, expressing it as external brightness in units of millilamberts (10/~ times pupil area in square millimeters). The adequacy of this unit to describe apparent brightness has been questioned by Stiles and Crawford (1933) who showed that the effectiveness of the light in producing a brightness perception falls off markedly when it passes through the more peripheral areas of the lens. Of course there are a number of immediately known factors capable of causing that percept: light scattering thru the peripheral lens, and altered perceptual capabilities of the peripheral retina, for example.

Logarithmic Categorization of Resolution and Contrast Sensitivity

In attempting to consistently utilize a uniform terminology regarding the combined visual performance characteristics for noting the degree of resolution as opposed to the degree of contrast sensitivity, the term visual acuity has been limited to describe spatial resolution under specified contrast conditions; the widely-accepted term 'logarithm of the minimum angle of resolution' (logMAR) is the optimal means of classifying the level or degree of visual performance, because of its continuous variable characteristics, which permit logMAR analysis through the use of parametric statistical means. The term contrast sensitivity has been used to describe the ability to distinguish small differences in contrast under conditions involving decreased luminance. Contrast Sensitivity can be documented in a logCS format representing discreet changes in target or letter contrast or under decreased luminance conditions. Contrast sensitivity also has been defined as a measure of the limit of visibility, when viewing low contrast patterns. The limiting degree of image fading, within a uniform background (as if driving in a fog), before two identical targets become indistinguishable from one another, is another means of describing contrast sensitivity.

Contrast sensitivity testing has proven itself as a penetrating performance diagnostic. However, it is utilized primarily within the research realm, due to its lengthy and cumbersome application and administration. Yet, a practical offshoot, the Rabin Small Letter Contrast Test (SLCT), is a proven established tool capable of easy application within the realm of an aviation-based eyecare clinic (Rabin, 1996). The SLCT is now available as a mobile tablet software system package, which also permits the random insertion and substitution of test letters on each line, serving to reduce the variable effect of subject test-letter memorization.

The SLCT's benefits have been identified as being three-fold (Rabin & Wicks,1996).

- as a measurement of the integrity of both the central and peripheral visual processing centers;
- as an indicator of detail-specific functionality (pertinent to facial recognition or detail-specific tasks); and
- an indicator of general figure/ground function (pertinent to movement within a complex environment).

There are several other contrast sensitivity tests which probe larger sized letters than the ten-letter, 20/25 sized letters of the SLCT. The Bailey-Lovie (1976) test uses five 20/40-sized letters (Rabin has since adapted that strategy in addition to his initial test arrangement), organized on a logarithmic contrast scale much as the Rabin SLCT had been patterned. This larger test letter size permits analytical probing into the mid-level, 'peak' aspects of the contrast sensitivity curve, providing completely different information on the visual system's functions than the SLCT. Established Army standards have varied little from the initial days of Army Aviation's nominal birth in the early 1920s. Among a number of visual requirements, prospective aviators had to meet rigorous Snellen visual acuity requirements, a high-contrast or supra-contrast test of visual resolution (black letters projected onto a brightly illuminated, highly reflective screen). The Army has many approved spectacle and contact lens wearers, as well as approved recipients of laser refractive surgery, with relatively few rated aviator refractive error restrictions. The single point of unwaivering central emphasis is that all ametropes must be correctable to a visual acuity of 20/20 or better in each eye (which equates to the resolving capability to 1 minute of arc, independent of the viewing distance). This acceptance of correctable refractive error is a more modern stance, taken in response to the relentless development of myopia (linked to advanced levels of education; hypothetically, a result of excessive over-accommodation when reading). Clear, single, binocular vision has always been an important aviation safety issue, with visual acuity, stereoscopic ability, and color sensitivity receiving the greatest amount of emphasis (and the least degree of leeway or flexibility) in terms of medical examination standards.

Safety of flight has always served as the strongest incentive to the strict monitoring of visual acuity (among all the other vision performance standards) throughout the course of an aviator's career. Over the many years since Army Aviation's inception, high-contrast Snellen visual acuity has served as the standard screening tool for the appraisal of visual function; as previously stated, the Snellen standard involves conditions of bright illumination under high contrast (i.e., black letters against a bright white background, either via projection on a highly reflective screen, or printed on a glossy white chart). In recent years a number of scientific investigators have sought to develop a more sensitive means of assessing visual resolution performance (e.g., Ginsburg, 1981; Bailey & Lovie, 1980; Rabin, 1994). In support of all the visual performance testing paradigms, contrast sensitivity testing in general has been shown to be superior at predicting a pilot's performance in detecting small, low contrast targets in simulators, as well as in the field, which is of direct importance to current military aviation DVE research efforts. Full scope contrast sensitivity testing under cycloplegic conditions had been proposed as a critical visual assessment task integral to the Army's Class 1 Flight Physical (Bachman and Behar, 1986). During a Class 1 flight physical, a topically applied 1% cyclopentolate solution serves to artificially-induce paralysis of the ciliary muscles of the eyes. The topical cycloplegic pharmaceutical primarily inhibits accommodation; a secondary effect is pupillary dilation. Cycloplegia produces a small reduction in contrast sensitivity under normal ambient conditions, and a greater reduction under glare conditions. For both conditions, the cycloplegic effect was greater for the higher spatial frequency (SF) gratings than for the lower SF gratings.

Continued research efforts in the mid-1980s were completed by Dr. Art Ginsburg, a by-then, well-known vision scientist in the U.S. Air Force (USAF) (1984). Then-MAJ Arthur P. Ginsburg stated that at that time, current research determined the inadequacy of high-contrast, photopic visual acuity testing. Dr. Ginsburg's conclusion was that current standards were not adequate to evaluate an individual's target capability over ranges of target size and contrast used in real bombing-run situations. At that time contrast sensitivity testing was in its relative infancy regarding practicality of testing techniques. However, Dr. Ginsburg applied a very apt analogy concerning the testing paradigm parallels between acoustic hearing tests and contrast sensitivity testing. Just as hearing tests make use of sound intensity and temporal frequency to measure audiometric sensitivity, visual contrast sensitivity tests use contrast and spatial frequency to measure visual sensitivity. Using Dr. Ginsburg's own prophetic words concerning the operational benefit of applying contrast sensitivity testing toward visual performance standards development: "Data are presented that reveal individual differences in contrast sensitivity among normal observers that have definite implications for visual performance in operational environments. Since these differences in visual sensitivity can relate to detection and recognition ranges, these data can then be transformed into time to perform certain tasks and lead naturally towards visual standards being based on task performance under operational conditions." Then, in the early 1990s, initial research by Dr. Jeff Rabin, using his Small Letter Contrast Test (SLCT) verified that test's sensitivity as more discriminating than traditional visual resolution testing (1994). It is also more responsive: to small amounts of blur, to subtle changes in the luminance of a stimulus, to vision with two eyes compared to one eye, and for identifying visual differences among pilot trainees. One intermediate goal of this standards-development effort is to use the SLCT as a means of quantifying the inferred degree of spherical aberration resulting from a cycloplegic application as part of a flight physical examination, using logCS index differences. A draft manuscript on basic spherical aberration data from 20 subjects is being prepared for the FY18 SPIE Conference. Alternatively, a number of investigators have converged on the idea that more detailed aberration-based categorical influences will be achieved using a wavefront analyzer during the visual exam portion of an overall physical examination. After this categorical determination of a modern vision resolution standard is completed, research subject examinations will serve to determine answers to these sorts of questions.

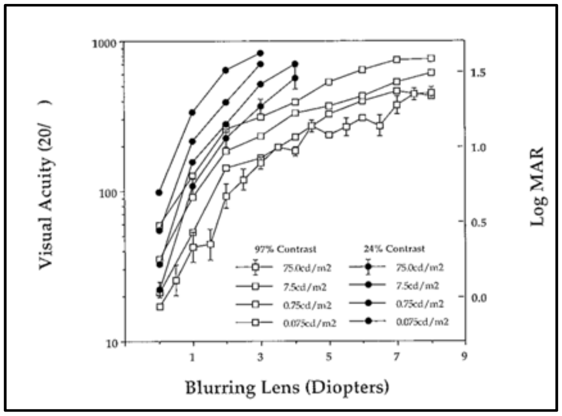

Figure 3. Log acuity as a function of blur at two contrast levels and four luminance levels.

It is important to comment at this point on the relationship of decreased luminance to conditions of decremented contrast. In discussing the concerns for both aspects of the visual environment, several other laboratory individuals had spoken up, questioning my separate classification of each issue as an important detail. It appeared that the prevailing internal attitude was that decreased luminance and decremented contrast had the equivalent effect on visual resolution, meaning each had an equal effect. However, Johnson and Casson (1995) noted after their research (as represented in Figure 7) and their review of others' research over a series of investigations, found that changes in background luminance, target contrast, and dioptric blur can all present different independent effects on contrast sensitivity. Their research used 4 expert psychophysical observers with a multiple number of repetitions. Yet, their evidence is so consistent, the conclusion regarding independent effects of each viewing condition aspect (blur, background luminance, and target contrast) cannot be disputed, which is important to the basic premise of this investigator's background assumption in justifying this assessment protocol, and an alternative vision testing standard for those anticipated to encounter DVE conditions in the course of performing their military duties.

Operationally aligned observational studies completed at Fort Benning under varied weather conditions by Dr. Richard Levine et al. demonstrated the distribution of young active duty Infantry Soldiers as either superior, average, or poor visual performers. This was specifically with respect to target detection, target recognition, and target identification of both friendly and opposition force individuals and combat vehicles. However, no screening tests had initially been established and standardized that were capable of consistently differentiating between those groups of operational visual performers. Without paired acuity-based and contrast sensitivity-based operational testing, there is no proof that the extremes of the low contrast / low luminance distribution would correlate or match operational visual performance. However, the advantage of being able to screen for superior visual performers during their initial flight physical, does evidence merit in support of further detailed study. Literature-based, external comparisons of the two acuity methods (i.e., full CSF testing vs. Rabin SLCT) emphasize statistically significant differences that have very real potential for future use in identifying superior visual performers. If this potential is realized, then standards for visual assessment in military aviation, and in the military specialty schools (e.g., airborne, Ranger, special operations), must be changed to enable detailed visual performance testing. Standard visual acuity (VA), which relies on a patient's ability to identify high contrast, black letters against a white highly-reflective background has long been recognized as the preferred means of measuring of visual function, yet it has no significance in determining vision under mesopic or scotopic conditions.

However, photopic visual acuity is only one aspect of overall visual performance or function (Hiraoki et al., 2015). For example, contrast sensitivity can provide additional important details regarding one's visual function under conditions of diminished luminance. Yet, even these singular numbers may not accurately reflect the entire spectrum of one's potential for comprehensive visual function. Under photopic conditions (i.e., bright lighting conditions) the retina's cone visual pathways represent the singular operational system underlying visual performance. Under scotopic conditions (i.e., dimly lit conditions) the retina's rod visual pathways represent the singular operational system underlying visual performance. During conditions of mesopic luminance, an intermediate lighting level between photopic and scotopic conditions, rod and cone pathways operate simultaneously in contributing to visual performance; the proportional contribution of each one is on an inverse sliding scale (Fein and Szuts, 1982). It is important to remember that the visual system operates over a remarkable range of lighting conditions. Under scotopic luminance conditions, rod visual performance can be summated across a wide range of retinal area, up to a maximum of approximately 1200 rods:1 retinal ganglion cell. Cones can have a 1:1 feeding into a retinal ganglion cell in photopic spatial resolution. The resolution decrease under mesopic and scotopic lighting is balanced by vastly increased sensitivity to changes in light level and motion (Kalloniatis and Luu, 2011).
For the safe execution of basic helicopter landings the primary source of visual information that is available to the pilots is a direct reflection of degree of visibility of the intended landing environment. Under normal weather conditions of a blue sky with unlimited visibility, aviation circles have used the term focal vision to make reference to the central 30 degrees or so of the visual field (vision scientists are much more conservative, attributing all the visual performance characteristics to the central 20 degrees of the retinal field). Focal vision is concerned with object detection (i.e., able to elucidate the presence of a faint object), recognition (i.e., able to clarify characteristics in order to separate friend from foe), and identification (i.e., able to name the specific aircraft originally detected minutes previously). These activities involve detail of varied complexity to include the application of high spatial frequencies. The information processed by focal vision is well represented in our consciousness, utilized on a frequent basis throughout the day. Therefore, it contributes to the conscious percepts of overall orientation and our position in space, and with reference to the horizon. During flights in Visual Meteorological Conditions (VMC), central vision allows distant judgment, color perception, and stereopsis, employing binocular cues of depth, vergence, parallax, and accommodation.

On the other hand, in the aviation community ambient vision involves broader areas of the visual field (including the visual periphery). It subserves spatial localization, orientation, and it primarily is involved with the position, motion and attitude of the individual/airframe as it is in motion within the environment. When under clear blue skies, ambient vision provides motion cues and position cues based on the visual identification of the horizon. In summary, focal vision orients the perceived object relative to the individual, whereas ambient vision orients the individual relative to the perceived environment. A common landing technique is to choose noticeable features on the ground (rocks, bushes, trees, fences, etc.) in order to set up the approach and land at the designated Landing Zone (LZ). An example of the type of visual reference necessary to control the aircraft near the ground is shown in the following figures (primarily the ground, and where it meets the sky - the horizon). These external ground-based features provide the pilot with necessary and valuable information for landing. However, the sudden loss of visibility or degraded visibility abolishes visual guidance references (pre-identified landmarks as stated above), other moving targets, distance and height perception that are essential to control the aircraft near the ground. As brownout is a sudden phenomenon that occurs close to the ground, there is little tolerance for error and inherent correction delay. Although the sudden loss of visual references would necessitate the transitions from VMC (Visual Meteorological Conditions) to IMC (Instrument Meteorological Conditions), there remains an inadequacy between task requirements (landing in a non-visual environment) and the lack of feedback for drift and height above terrain, especially in legacy aircraft equipped with only standard flight instrumentation. Delayed detection of lateral drift means corrective actions may not be implemented in time to avoid disaster.

Figure 4. Examples of rotor downdraft. The rotor downdraft, in combination with the rotor tip vortex, creates an effect that scatters loose ground material (sand and/or snow, in the cases shown) [from the Army Combat Photographer collection].

Whiteout and brownout landings pose a similar problem to the helicopter pilot. As the aircraft descends closer to the ground, rotor downwash stirs loose sand and/or snow, which is drawn into the rotors and drawn outward and upward in a circular effect, serving to obscure vision.Visibility is significantly reduced and pilots must adopt alternative landing strategies. Whiteout mishaps have been reported by Scandinavian and Canadian members of the Nordic Task Group, as have brownout mishaps reported by U.S. Forces in SouthWest Asia.

Importance of Pre-Flight Inspections

Paraphrasing portions of NATO HFM-162 (2012), during flights under Instrument Flight Rules (IFR) in Instrument Meteorological Conditions (IMC), pilots should be able to read the instrument displays that provide the necessary, yet basic, spatial awareness information with confidence. Pilots are trained to trust their instruments and ignore their physiological system feedback sensations during landing, even if external visual cues are available. This training is to ensure aviators actually do concentrate on their flight instruments. Those internal signals that everyone is trained to ignore are nonetheless extremely influential in their pull, partly because of their lengthy history at correctly interpreting conditions that are occurring throughout a lifetime of ground-limited input. Yet, those valued details when ground-limited are of absolutely no utility in the air. Therefore, preflight validation that the instrument displays are functioning properly, ensuring that they are providing veridical flight parameters is an absolutely life-saving pre-flight procedure. However, peripheral (ambient) vision can facilitate the detection of drift and height above terrain which are the most critical information required during take-offs and landings; making supplemental visual information of considerable value. The helicopter, by nature is an unstable platform. Pilots have to "work" persistently with their controls in order to gain and maintain stability. Without inputs to the controls through either the Automated Flight Control System (AFCS) or hands-on control, the position of the helicopter in three dimensional space can be maintained for only a very short period of time. Usually, this period of deliberately controlled stability is much shorter than the time that it takes to proceed to a full landing the helicopter (and depends on the specific airframe and the actual environmental conditions encountered).

The landing procedure, descending and landing from a stable hover is challenging in-and-of itself. In order to proceeding from a stable hover to a final landing on the ground requires numerous actions within a small window of time, and in a select sequence. The helicopter pilot must reduce the torque (or force). The act of reducing force, within a fraction of a second, immediately requires a change of tail rotor power. The amount of tail rotor power reduction is proportionate to the amount of main power reduction (or torque), which is (in turn) determined through feedback sensory details culminating in visual information obtained by the pilot. The impact of a change in tail rotor power is to create drift, which is compensated by moving the cyclic, in order to influence the requirement of power. This process requires "working" of the controls by the pilot in order to maintain stability. Moreover, as the helicopter is closer to the ground, the rotors are further influenced by the turbulence of air impacting the ground and their subsequent reflection off the ground's surface. If mission requirement dictates that the landing procedure were to be sped up (i.e., a quick reduction in power), it would create a greater disturbance. The fidelity of prior generational helicopter instrumentation was generally not sufficient to execute instrument landing in remote and unfamiliar Landing Zones (LZ), particularly while under DVE conditions (NATO Task Group HFM-162, 2012). Brownout causes a loss of visual reference that is of progressively greater import the closer to the ground one becomes, allowing a progressively decreasing tolerance for error, and even less tolerance for any decisional correction delay below that required for situational awareness. Any decisional delay in attempting a corrective action will be compounded by ever-present perceptual inadequacies of the vestibular system. The sudden loss of visual references induces major changes in the piloting process, which in-turn increases the opportunity for SD. The discrepancy between task requirements (landing in a remote location under DVE conditions), along with insufficient information from legacy instrumentation can further compound the problem.

Engineering and Physiological Risks

The potential engineering-based risk mitigating strategies for rotary-wing brownout take-offs and landings could fall into two broad categories:

1) Technology development to overcome the environmental limitation described above under DVE conditions, for example, "see through" or "dust-penetrating" technology.
2) Technology development to overcome the physiological limitation under DVE conditions, for example, provide pertinent information, in an intuitive manner (better

landing symbology systems or other sensory displays) to the pilot in order to compensate for the lack of external visual cues.

None of the above engineering-based strategies for coping with DVE grasp the physiologic-specific demands of mesopic conditions, which represent this intermediate region of overlapping photoreceptor function, which is the research area of interest that's currently subjected to this concentrated review and recommendation. Given the variety of its unique complexities, the large temporal differences existing between rod-generated and cone-generated signals are of primary importance (Umino, Solessio, & Barlow, 2008). These differences are caused, in part by differences between the initial responses of the rod and cone photoreceptors themselves. Overshadowing the differing photoreceptor response differences are response processing differences within the post-receptoral retina (i.e., bipolar cell responses), as well as the cortical pathways (Yang & Wu, 1997). These differing mesopic threshold responses (photoreceptor responses, post-receptoral retinal responses, and higher cortical responses) all complicate this area of visual function, given its importance within the Army aviation community (Fahey & Burkhardt, 2001). Visual conditions labelled as a 'degraded visual environment' (DVE) have pressed vision scientists to develop basic understanding of optimal visual performance standards. Because visual disturbances at night are critically related to visual function, the lack of studies seeking the establishment of performance standards relevant to mesopic functional performance represents a significant gap in the overall vision science literature, particularly military-based references. Under low luminance conditions (such as night driving, or driving in fog, or driving in heavy rain, or flying a helicopter under these conditions), luminance from an object is often within the range of mesopic vision (-3 cd/m^2 to 3 cd/m^2). Under very low luminance circumstances, visual acuity plays a less important role than the ability to recognize weak target contrast changes (Johnson & Casson, 1995). However, there were no standard contrast sensitivity scales in normal persons within the mesopic luminance exposure range until 2015, when Hiraoki et al. conducted their initial study using 68 normal, healthy subjects. They evaluated visual responses in these normal subjects on both a 'within-subjects basis', and on a 'between-subjects basis' while analyzing visual performance variability under mesopic conditions as a function of both time and luminance.

Alternative Factors

Accessory physical factors other than optical have a positive influence on contrast sensitivity in mesopic conditions (i.e., the degree of macular pigmentation). Macular pigmentation has been shown to have a positive influence on contrast sensitivity performance (Jia et al., 2017). The concept is related to macular pigment absorption of scattered light falling on the retina, thereby artificially increasing the signal to noise ratio of retinal illuminance. Under ever worsening conditions, contrast sensitivity of affected individuals will progressively improve, as compared to others with normal or no macular pigmentation. Arranz et al. discussed the relative significance of optical and neural mechanisms in letter contrast sensitivity under 26 different conditions of test luminance and surround luminance lighting (test luminances from 10 cd/m^2 to 600cd/m^2), and surround luminances (from 1 cd/m^2 to 600 cd/m^2). The results reveal a significant influence of optical factors (pupil size variations and glare effects) on contrast sensitivity when the surround luminance changes, and a dominance of neural effects when the test luminance changes (Arranz et al., 2014). Today's photopic Snellen visual acuity requirements stipulate the use of a series of black letters projected onto a brightly illuminated, highly reflective screen as a high-contrast test of visual resolution within brightly lit surround conditions. On only rare occasions, like under acuity testing, does one encounter photopic chart conditions under photopic surround conditions, with 100% contrast black target lettering. “Normal” visual acuity is frequently considered to be the ability to recognize an optotype or standardized letter, when it subtended 5 minutes of arc; in the case of the United States test chart, each component of the letter “E” (three horizontal bars and two spaces) subtend one minute of arc. In the United States, the Snellen chart depicts normal acuity as 20/20 (using a nominal test distance of 20 feet). In the UK, the Snellen chart depicts normal acuity as 6/6 (using a nominal test distance of 6 meters). The log of the minimal angle of resolution or logMAR (i.e., one minute of arc) is recorded as 0.0. The Army has relatively few rated aviator refractive error restrictions. The single point of emphasis is that all ametropes must be correctable to a visual acuity of 20/20 or better in each eye. This acceptance of correctable refractive error is a more modern stance, taken in response to the relentless development of myopia (linked to advanced levels of education; hypothetically, a result of excessive over-accommodation when reading). Clear, single, binocular vision has always been an important aviation safety issue, with photopic visual acuity, stereoscopic ability, and color sensitivity receiving the greatest amount of emphasis in terms of medical examination standards development. Regardless of the fact visual acuity standards are relatively unchanged since their origin, today’s survivability difficulties secondary to flight mishaps resulting from a degraded visual environment (DVE) and Controlled Flight Into Terrain (CFIT) have taken an unacceptable toll on human life. Of all the vision tests developed since the 1870s, many held potential military applicability. The Rabin Small Letter Contrast Test (SLCT) appears to have gained the widest military recognition, with its joint applied use in NVG testing, and its adoption within the most recent U.S. Air Force Medical Standard publication (Subramanian et al., 2003). Current testing versions are on a computerized pad (e.g., iPad), which enables variability of test chart brightness, in addition to variability of the general test environment’s surround brightness, enabling the tester to take advantage of the work of Arranz et al. (2014), above.

Wave-front aberration metrics, however, could very well provide an improved standard or correlative fit for both high-contrast mesopic visual sensitivity, and low-contrast scotopic visual sensitivity (Pesudovs et al., 2006). In support of wave-front aberration metrics, Pesudovs et al., explored whether photopic high contrast visual acuity is an appropriate visual performance reference, or alternatively, whether mesopic and/or low contrast testing provides any advantage. Visual acuity was measured under four conditions: photopic high contrast conditions, photopic low contrast conditions, scotopic high contrast conditions, and scotopic low contrast conditions. Variables were tested for compliance with normality, and transformed if required. Linear regression and Bland-Altman 95% limits of agreement (+/- 1.96 SD) were used to examine relationships between the conditional variables, acuity, and wavefront aberration metrics. The two photopic measures were poorly distributed, but the two scotopic measures were normally distributed (a characteristic that many of the previously discussed studies also exhibited). While strong correlations existed between the visual acuity variables regarding photopic testing, low contrast and/or scotopic acuity testing provided significantly different references regarding wavefront metrics. Consequently, the conclusion was reached that physical optics effects (natively inherent to the eye) provided improved correlation with visual performance under both scotopic-based low-luminance and low-contrast conditions. Therefore, wavefront aberration metrics were their recommended visual performance test for scopic conditional testing, which was most predictive of visual capability under scotopic DVE visual performance conditions.

Information Theory

Information theory may be applied to the sensory continuum of mesopic / DVE visual performance, in order to monitor and eventually predict the amount of information needed for reliable extrapolation modeling of the visual performance thresholds of a perceived sensory stimulus. However, the number of experimental trials that are required to produce a result of statistical significance is extraordinarily high, in the order of 10^4 number of trials to achieve statistical significance. Common experience has established that a human subject can retain peak concentration long enough to produce only about 100 to 200 trials per day when conducting basic threshold perception data-gathering responses (although some investigators do press for as many as 500). In order to provide the missing data between the last trails obtained, and the final modeled value that's predicted, one can follow the process established by Houtsma (1983), by utilizing a computer simulation to run the subsequent computer extrapolated data sets. One simulator can model the subject, providing responses that the subject would have made, had it been possible to continue the human testing protocol over a period of months or even years, obtaining highly correlated data compared to high data values obtained from a single subject, who is affected by fatigue, loss of focus, and eventual disinterest.

Baccus and Meister (2002) examined how the visual system adapts to the magnitude of contrast intensity fluctuations, which begins in the retina, as do the initial dark adaptational processes. Following the switch from a low-contrast environment to one of high contrast, ganglion cell sensitivity declines in two distinct phases: a fast change occurs in < 0.1 second, and a slow decrease occurs over ∼10 seconds. To examine where these modulations arise, Baccus and Meister recorded intra-cellularly from every major cell type in the retina. Certain bipolar and amacrine cells, as well as all ganglion cells, are able to effectively adapt to contrast changes. Generally, these neurons have demonstrated both fast and slow adaptation characteristics. The fast effects of a contrast increase included: accelerated kinetics, decreased sensitivity, and a depolarization of the baseline membrane potential. Slow adaptation did not affect kinetics, but produced a gradual hyperpolarization. It is this hyperpolarization which accounts for the slow adaptational alteration in the spiking output of ganglion cells. The objective or the protocol goal was to develop an understanding of the visual processing variability functions that directly contribute to both optimal, and less than optimal, unaided contrast sensitivity performance (particularly while under DVE conditions). Contrast sensitivity is an individualized visual performance characteristic resulting from several unique CNS-processing approaches by the visual system. By stratifying individual contrast sensitivity threshold sensitivity, it may be possible to determine the underlying central nervous system processing functions responsible for individual variation. Anatomical-, visual-, and psychophysical analyses of sample subject stratification categories will pinpoint the underlying contributors to the exhibited thresholds of the better DVE visual performers. Furthermore, the intention is to link those subjective response extremes to their underlying governing factors (e.g., nutritional influences, neural factors tied to decreased illuminance, loss of fine ocular control – accommodative, pupillary, and fixational drift errors, extra-ocular muscle control variance) in order to gain control of their exhibited end-result visual performance. Previous studies related to gaining an understanding of the underlying governing factors are highly varied in their approach and results. Solé et al. (1984), found cyaninoside chloride to significantly improve photopic visual acuity ($p < 0.05$) in 31 clinical subjects chronically suffering from poor vision under low luminance conditions. Cyaninoside chloride treatment also improved visual function related to mesopic and scotopic conditions, as well ($p < 0.01$). There were also significant differences between the control and treatment groups regarding the velocity of visual adaptation in adapted electro-retinography. Their study demonstrated the therapeutic value of cyaninoside chloride for the treatment of functional vision disturbance under mesopic and scotopic conditions. Beyond those goals and standards that are to be approached, the end point of this research is to understand each individual's native (natural) maximal visual performance capability, and to apply that toward a military duty (e.g., sniper or pilot), in order to maximize an individual's specific skill or ability. When feasible, the intention to seek to expand an individual's performance characteristics is almost always a motivational stimulus. However, a medical research goal of performance enhancement is not necessarily within the expected research performance limits of our current mission. The brain's cortical processing centers cross-connect along numerous channels, allowing signal-gating, which enables signal refinement. Arranz et al. (2014) demonstrated that decreases in visual resolution occur at lower light levels resulting from central neural-control factors associated with decreasing retinal luminance and *not* optical blur secondary to increased pupil size, and an induced myopic shift. Microfluctuations in accommodation within a decreased illuminance setting directly further contribute to decreased visual resolution (Arumi et al., 1997; Gray et al., 1993). Similarly, eye movement variability also increases in the dark, directly contributing to increased fixational instability and decreased visual resolution (Doma & Hallett, 1988). A number of complex theories regarding the underlying cause of mesopic contrast sensitivity resolution variation are under continued assessment. Certainly, each factor could partially contribute to reduced visual resolution under mesopic conditions. Alternatively, each could play a varying role, dependent upon the specific conditions encountered, and the demands made upon the visual system at that particular moment. Independent of all these established contributors to performance variation, and perhaps overshadowing them are the combined influences of fatigue and aging.

Determination of the underlying contributors toward varied performance ability must be analyzed within the context of established visual performance ranges. In the final analysis, the current approach is oriented toward establishing standardized levels of visual performance sensitivity at well beyond the normally expected ranges of human visual sensitivity. This approach will meet the newly emerging gap falling between modern-developed instrumentation and current (possibly outmoded) human visual performance standards (Hohberger et al., 2007). Consequently, fund investment in this human dimension 'technology' to identify those individuals with superior contrast-sensitive visual resolution, and define the underlying aspects of the visual system which provides these individuals with superior ability, could very well prove to be the least costly, and most effective, long-term solution toward the provision of safe, effective combat flight under degraded visual conditions. Photopic, scotopic, and mesopic contrast acuities are subject to differing post-receptoral pathways through which the rod and cone signals are transmitted. As a complicating consideration for mesopic performance, results will depend not only on the luminance level, but also on the spectral content of the stimuli used to probe performance, the retinal location being stimulated, the spatial frequency content of the stimulus, as well as the temporal frequency content. All these must be considered when attempting to derive (or to apply) a luminous efficiency function for mesopic vision. Although strongly correlated with one another, and considered by some to be two sides of the same 'coin,' low contrast sensitivity testing and mesopic acuity testing each provide differing informational details. Wave aberration metrics better correlate with low contrast scotopic acuity, making that as the objective visual performance test of choice. (Pesudovs et al., 2004).

Critical Aviation-Based Visual Performance Issues

Factors that appear to be shaping synaptic signal transmission from rods and from cones to bipolar cells are not controlled by the rate of neurotransmitter release, but by the speed of neurotransmitter vesicle replenishment (Burkhardt, Hattendorf, Weis, & Fasshauer, 2008). This is reminiscent of age-based renewal delays concerning dark adaptation performance, which is dependent upon the renewal rate of 11-cis retinal, not by the rate or strength of retinal signaling (Lamb, Cideciyan, Jacobson, & Pugh, 1998; Leibrock, Reuter, & Lamb, 1998). A wide-ranging combination of issues can compound to adversely influence contrast sensitivity under mesopic conditions. One of the major influences not previously discussed is the individual's age with respect to the effective use of both head- and eye-movement, in-tandem. Infrared scene and symbology information is normally seen on the primary flight display of a helicopter, or on its flight simulator instrument panel emulation. A combined head and eye movement analysis introduces an in-tandem age-based experiential factor not seen in younger subjects. Whether this improved in-tandem performance accuracy is a factor of improved muscle memory correlation benefitting all aspects of eye and head movement, or a reflection of fixational registration of a specific type of aircraft's cockpit layout is still being debated. Nonetheless, these differential underlying mechanisms could be easily tested against one another.

Analytical Age-Dependent Model

Joulan, Brémond, and Hautière (2015), aware that CSF efficiency declines with age, sought to develop an analytical age-dependent model of contrast sensitivity functions in an aging sample (Joulan, Brémond, & Hautière, 2015). Age-dependent analytical models of cone densities combined with the ganglion cell densities, were found to directly reflect on both the age-based optical Modulation Transfer Function (MTF) and the age-based neural MTF. Consequently both optical noise and neural noise were proposed as the underlying causes of the age-dependent CSF changes, which they feel would assist in designing real-time, age-dependent display applications to assist in counteracting age-based deficits. They did not have rotary wing aircraft cockpit displays in mind when they made this suggestion. However, their proposed system appears to be an excellent fit for helicopter display utilization. A wide variety of additional factors, all either optically- or neurologically-based in nature can cumulatively affect visual performance, as well. However, neural processing applications have been judged to be more likely to partially counterbalance those confounding effects from anatomical/optical variations. This neurological adaptational ability has previously been identified as a critical factor related to visual recovery from refractive surgery. This concern over age-based deficits is not necessarily an issue pertinent to the active military, since most Soldiers over the age of 48 or so are not deployable in active flight positions. The majority of age-based deficits are not readily demonstrable under the age of 50 years. Regardless of that thought, seeking to benefit from experiential and cockpit-designed improvements as a function of individual photoreceptor and ganglion cell densities is worth considering, when seeking to maximize combat survivability within a DVE engagement. Allard et al. (2013) and Arranz et al. (2012) evaluated the relative significance of optical and neural mechanisms on letter contrast sensitivity under different conditions of environmental lighting. Studies were carried out on 26 eyes with normal ocular health. Sixteen lighting conditions were obtained by combining different test luminances (from 10cd/m^2 to 600cd/m^2) and surround luminances (from 1cd/m^2 to 600cd/m^2). The results revealed a significant influence of optical factors (e.g., pupil size variations, and glare effects) on contrast sensitivity when the surround luminance changes; as well as a dominance of neural effects when the test contrast changes. Rabin and Wicks (1996) presented recent evidence suggesting that the Small Letter Contrast Test (SLCT) is more sensitive than traditional Snellen visual acuity testing, when referring to defocus, luminance, binocular enhancement, and visual differences among pilot trainees, even when a normal level of room illumination is used. The SLCT has been found to be more sensitive than Snellen VA to spherical and astigmatic blur, decreased luminance, in addition to vision with two eyes vs. one eye. Additionally, a greater sensitivity of the SLCT endured despite correction for variability. The SLCT was more sensitive than standard tests to visual loss from early cataract, keratoconus, corneal infiltrates, edema, and amblyopia, as well (Rabin, 1994; Rabin, 1995). All of the above were initially-derived test benefits of the SLCT; over the past 15 years there have been a number of refinements and improvements such that this is undeniably the best visual function test to use when examining individual performance abilities under the stresses of DVE.

Hiraoka et al. (2015) concluded, after reviewing a range of classical studies, that factors other than refraction influence contrast sensitivity under low luminance conditions. The brain's visual cortical processing centers cross-connect along numerous channels, allowing the application of signal control or signal-gating processes, which enable complex signal refinement. They theorized that decreases in visual resolution occur at lower light levels because of neural factors associated with decreasing retinal luminance, and not optical blur secondary to an increased pupil size, or not even due to an induced myopic shift. Microfluctuations in accommodation within a decreased luminance setting also directly contribute to decreased visual performance. Similarly, eye movement variability (e.g., saccades and smooth pursuit) exhibit increases in the dark, directly contributing to increased fixational instability and decreased visual performance. A number of theories regarding the underlying cause of mesopic contrast sensitivity resolution variation are under continued assessment. Certainly each factor partially contributes to reduced visual resolution under mesopic conditions. Alternatively, each could play a varying role, dependent upon the specific conditions encountered (i.e., stimulus size, color contrast content, etc.), and the demands made upon the visual system. Independent of all these established contributors to performance variation, and perhaps overshadowing them are the combined influences of fatigue and ageing, which have not yet been fully investigated other than commented on earlier, by Joulan, Brémond, and Hautière (2015). As a final point, Hertenstein et al., asked: "Can photopic contrast sensitivity testing act as a surrogate measure for mesopic contrast sensitivity testing, at least for screening purposes?" Mesopic contrast sensitivity (CS) testing approximates low-lighting conditions, however mesopic CS testing entails dark adaptation, as well (Hertenstein, Bach, Gross, & Beisse, 2016). By not accounting for individual variability in dark adaptation facility, the final contrast sensitivity data will likely be a representation of lower sensitivity responses than otherwise would be obtained. Both investigators noted that receptor-specific diseases are expected to exhibit a dissociation of photopic and mesopic sensitivity. However, they asked if photopic CS in a normal individual could act as a surrogate measure for mesopic CS, at least for screening purposes? Their answer was: while mesopic and photopic contrast sensitivities achieved a fair degree of correlation ($R = 0.51$; $p < 0.01$), only 27 % of their variance is in common. In particular, subjects with high photopic CSF results will be equally likely to have either low or high levels of mesopic CSF. Therefore, photopic contrast sensitivity tests simply cannot serve as surrogate measures for mesopic contrast sensitivity or contrast sensitivity performance. Consequently, the optimal testing condition in predicting one's degree of DVE performance, or lack of it under mesopic conditions is through use of the Rabin SLCT.

General Summation

Mesopic Visual Performance Options

Mesopic visual performance assessment results appear to be on a complex sliding scale that is subject to several unique known and unknown determinants, which control the final levels of categorical performance. It is further suggested that logically, a number of unknown determinants or controlling factors must be understood as well, before a complete valuation of mesopic visual performance standards are to be derived. However, in the interim a general framework can be prepared against which the more complex details can be inserted. Johnson and Casson (1995) noted that although previous investigations have reported that changes in background luminance, stimulus contrast, and dioptric blur can each affect contrast sensitivity independently, it has not been shown how these three variables interact to influence visual resolution. This is a particularly important issue if one is interested in predicting how individuals with different refractive characteristics will be able to perform acuity-based tasks in degraded visual environments characterized by a combination of low background lighting with decreased contrast. In summation, the conceptual framework for providing a global assessment of threshold-linked visual performance is dependent, to varying degrees of influence, upon these two primary factors:

- optical factors (e.g., pupil variations, corneal shape factors) primarily responsible for affecting visual resolution as measured via the logMAR format, and…
- neural adaptational factors, which are primarily operant under varied contrast conditions, as measured via the logCS format.

The establishment of contrast sensitivity norms or standards regarding acceptable contrast sensitivity performance levels under mesopic conditions would assist in determining if an exhibited decrease in dark adaptation or contrast sensitivity is pathologic in nature. Alternatively, determination of acceptable variance in human tolerance variability to dim, poorly illuminated conditions would also serve as an excellent reference point. Finally, the utilization of high-contrast photopic visual acuity as the "gold-standard" for visual performance across numerous agencies, suggests the prevailing attitude that mesopic and scotopic conditions have been thought to be irrelevant regarding visual performance standardization. Photopic high contrast visual acuity is not an appropriate visual performance reference when predicting one's visual performance under degraded visual conditions (Bartholomew, Lad, Cao, Bach, & Cirulli, 2016). Additionally, mesopic and/or low contrast visual testing DO NOT correlate at all well with high contrast visual performance testing, nor will high contrast photopic visual performance testing correlate well with dark adaptation facility testing (Barrio, 2015).

Conclusions

Critical Indices of Visual Performance Variability

- Photopic visual acuity alone cannot consistently predict one's visual abilities under conditions of DVE (i.e., under mesopic and scotopic conditions). Therefore, revision of the U.S. Army Regulation 40-501 visual performance standard for visual resolution must include mesopic visual performance testing.

- Contrast sensitivity-based tests (i.e., contrast sensitivity testing) under decreased luminance are the most efficient means of identifying those with superior mesopic visual performance abilities. However, the SLCT and the Pelli-Robson test systems probe vastly different aspects of the contrast system, and should be used sequentially in-tandem.

- Despite the numerous accessory factors affecting mesopic acuity, "wavefront aberration metrics" better correlate with low contrast scotopic acuity, making this the visual performance test of choice for predicting visual performance under severe or extreme DVE conditions. Wavefront aberration metric testing should be reserved only for special mission cases.

Suggested Army Regulation 40-501 Visual Performance Standards

Findings Based on a Combined Meta-Analysis and Literature Review

In a NASA-Ames occupational vision standard review the observation was made that a great many visual acuity standards, including aviation-based standards, have not been empirically derived, appearing to be primarily based on an aggregate of expert opinion only, rather than job-specific empirical testing, or by occupation conditionally-based task analysis (Beard, Hisle, & Ahumada, 2002). Canadian divers, reportedly anticipating the occasional surface engagement under enemy fire, are required to possess an uncorrected visual acuity of 6/60 or better in UK notation, which is equivalent to 20/200 or better in US-Snellen notation. In response to NASA's expert opinion observation, three studies had been located that determined mesopic visual acuity; the mean mesopic acuity of those studies involving 338 subjects, was determined to be logMAR 0.48. That logMAR sensitivity value is equivalent to a mean mesopic Snellen visual acuity of 20/60. Based on this multi-sample mean mesopic visual sensitivity result, the suggested Class I Aviation Acuity Standard is determined to be slightly less sensitive than the multi-study mean, noted above. Therefore, the suggested Class I Aviation Mesopic Acuity Standard of 20/100 in Snellen notation, or at a sensitivity level of logMAR 0.70 is endorsed, until operational based, empirical testing permits a revision.

Using the current photopic standard Snellen Acuity Chart

- Required photopic acuity must be 20/20 or better (with or without correction). In logMAR terminology, a logMAR of 0.0 is equivalent to 20/20. 20/16 or better will result in a negative logMAR of -0.1 or less (refer to the conversion chart to the right of the Snellen Chart).
- Under **mesopic luminance**, 20/100 or better, or a logMAR of 0.70 or lesser value

Using the logCS SLCT chart

Fourteen lines, with 10 letters per line at 20 feet:

- Under **photopic luminance**, the logCS must be at least 1.0 or greater (That is Row 11 – Row 14)
- Under **mesopic luminance**, the logCS must be 0.60 or greater (That is Row 8 – Row 14)

Figure 5. Small Letter Contrast Test (SLCT)

Wavefront aberration metric testing is optimal for scotopic conditions when a visual Strehl ratio is computed in the spatial frequency domain (VSOTF) of 0.22, which represents the break-point separating better scotopic performers from the others.

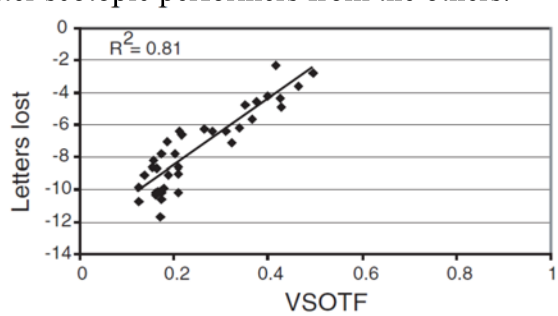

Figure 6. Visual Strehl Computation. The best scotopic Optical Transfer Function Metric (OTFM) that was tested against the visual Strehl ratio computed in the spatial frequency domain, possessed an optimal $R^2 = 0.81$. The clear division of response differentiation between good visual performers vs. poor visual performers occurs at a VSX of 0.22.

VSOTF - visual Strehl line (plotted above) using the best computed frequency domain optical transfer function (OTFM), plotting letters lost as a function of the visual Strehl ratio (VSX) reveals an $R^2 = 0.81$, when the visual Strehl ratio is computed in the spatial domain. There are 6 other metrics that can account for 70% or more of the variance, however the VSOTF accounting for 81% of the variance is the optimal analytical means of determining the key separation point.

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Abbreviations

AR	Army Regulation
CNS	Central Nervous System
CONOPS	Concept of Operations
CRD	Capabilities and Requirements Directorate
CS	Contrast Sensitivity
CSF	Contrast Sensitivity Function
DHA	Defense Health Agency
DVE	Degraded Visual Environment
L-Cones	Long wavelength-sensitive, or red-sensitive, cones
LED	Light Emitting Diode
logMAR	Logarithm of the Minimum Angle of Resolution
MAR	Minimum Angle of Resolution
M-Cones	Medium wavelength-sensitive, or green-sensitive, cones
MTF	Modulation Transfer Function
ND	Neutral Density
fNIRS	functional Near Infra-Red Spectroscopy
NIRT	Near-Infra-Red Laser Therapy
OTFM	Optical Transfer Function Metric
OIF / OEF	Operation Iraqi Freedom / Operation Enduring Freedom
RDECOM	Research, Development and Engineering Command
RDT&E	Research, Development, Test and Evaluation
S-Cones	Short wavelength-sensitive, or blue-sensitive, cones
SLCT	Small Letter Contrast Test
TRADOC	Training and Doctrine Command
USAACE	U.S. Army Aviation Center of Excellence
VA	Visual Acuity
VSOTF	Visual Strehl ratio using the best OTFM
VSX	Visual Strehl ratio computed in the spatial domain

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