USAARL Report No. 2017-17

Varied Human Tolerance to the Combined Conditions of Low Contrast and Diminished Luminance: A Quasi-Meta Analysis

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Visual Protection and Performance Division

August 2017

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REPORT DOCUMENTATION PAGE		*Form Approved OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
30-08-2017	Final	

4. TITLE AND SUBTITLE
Varied Human Tolerance to the Combined Conditions of Low Contrast and Diminished Luminance: A Quasi-Meta Analysis

5a. CONTRACT NUMBER N/A
5b. GRANT NUMBER N/A
5c. PROGRAM ELEMENT NUMBER N/A

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

5d. PROJECT NUMBER N/A
5e. TASK NUMBER N/A
5f. WORK UNIT NUMBER N/A

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

8. PERFORMING ORGANIZATION REPORT NUMBER
USAARL 2017-17

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Medical Research and Materiel Command
504 Scott Street
Fort Detrick, MD 21702-5012

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
Human physiological tolerance to performance-based stressors or obstacles is an important issue common to every cellular and neurologic bodily system. Visual performance assessments are on a sliding scale, subject to known determinate factors, which control the final level of actual performance. There logically are also a number of unknown determinants or controlling factors that must be understood, as well. Over the years a host of visual performance studies have separately evaluated the effects of varied illuminance on acuity, as well as the effects of varied target contrast on acuity. However, few have looked at the combined challenge of altered contrast, while subject to decreased retinal illuminance. It wasn't until approximately 2002, when a great many refractive surgery post-operative evaluations began assessing visual performance under varied luminance and contrast levels. This research effort will review any and all studies on visual performance under either, or both of these two conditional variables (i.e., decreased target contrast in conjunction with conditions of decreased luminance, as well as each individual condition).

15. SUBJECT TERMS
visual acuity, contrast sensitivity, diminished luminance, visual performance, meta analysis

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	49	Loraine St. Onge, PhD
					19b. TELEPHONE NUMBER *(Include area code)* 334-255-6906

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

REPORT DOCUMENTATION PAGE (SF298)
(Continuation Sheet)

14. ABSTRACT (CONTINUED).

Current knowledge is unable to establish validity regarding either of the following conditional challenges: either both visual performance conditions are completely independent of one another, exhibiting no evidence of interaction, or both interactive inhibition and/or interactive summation, can occur at varying performance levels, dependent on the specific operant conditions. Consequently, future research will seek out numerous potential controlling factors (e.g., functional, anatomical, neural, and optical indices of variability will be fully investigated) to determine the critical governing characteristics, including an understanding of the timing variances of those characteristics.

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Introduction

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 a supposedly excellent measure of visual function. However, VA is only one aspect of overall visual function (Hiraoka, Hoshi, Okamoto, Okamoto, & Oshika, 2015). For example, contrast sensitivity (CS) 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 sole operational system underlying visual performance. Under scotopic conditions (i.e., dimly lit conditions), the retina's rod visual pathways represent the sole operational system underlying visual performance. During conditions of mesopic luminance, an intermediate lighting level between the photopic and scotopic conditions, rod and cone pathways operate simultaneously (or concurrently) in contributing to visual performance. Additionally, 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 rod outputs feeding into one ganglion cell, as opposed to 1 cone output feeding into one ganglion cell under photopic conditions. This resolution decrease in the rods is balanced by a vast increase in both light sensitivity and motion sensitivity. Mesopic conditions representing this intermediate region of overlapping photoreceptor function is the research area currently subjected to this concentrated review.

Given the variety of their unique complexities, the large temporal (or timing) differences that exist between rod-generated and cone-generated signals are of primary importance. 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 along the post-receptoral internal signals of the retina, as well as within the occipital cortical pathways of the brain. These differing mesopic threshold responses (photoreceptor responses, post-receptoral retinal responses, and higher occipital cortical responses) all serve to complicate this area of visual function that has recently become of interest to the military, which has been labelled as a degraded visual environment (DVE), regarding visual conditions labelled as a degraded visual environment (DVE). Because minor disturbances at night are critically relevant to visual function, the lack of studies seeking to refine the standards involved in mesopic vision represents a significant gap in the military's overall vision science program.

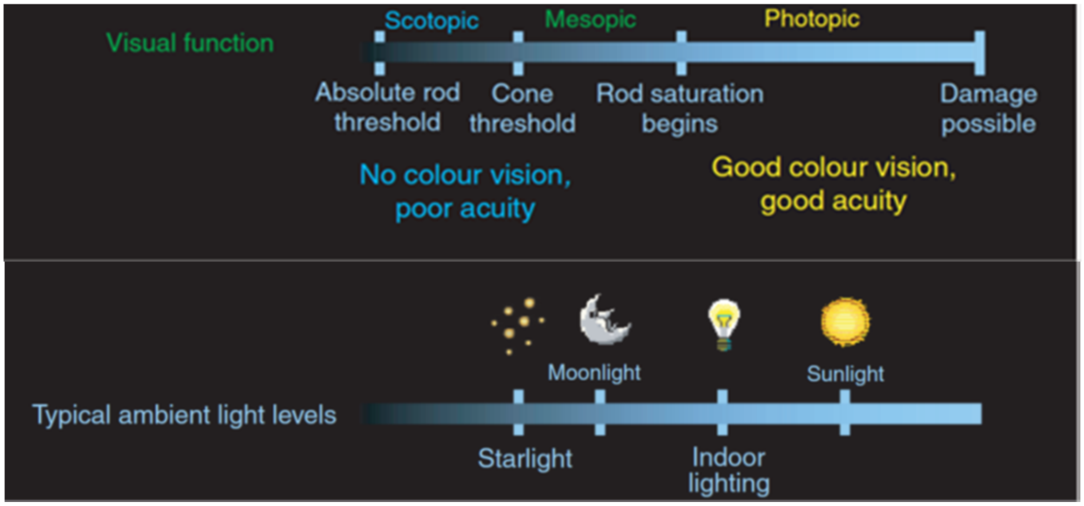

Figure 1. Compares typical ambient light levels with their corresponding visual performance functions. Excerpt from: Stockman, A., & Sharpe, L. T. (2006). Into the twilight zone: the complexities of mesopic vision and luminous efficiency. *Ophthalmic and physiological optics, 26*, 225–239.

Under combined conditions of low luminance with low contrast (such as night driving, driving in fog, or night driving in heavy rain, or flying a helicopter under these conditions), is the most challenging when the range of mesopic luminance is: log -3 cd/m^2 to log 3 cd/m^2 (as seen below respresented by the green Mesopic text). The scotopic, mesopic and photopic regions are defined according to whether rods alone, rods and cones, or cones alone, are the primary functional photoreceptor. The conversion from scotopic to photopic values assumes the use of a white International Commission on Illumination (CIE) Standard Illuminant D65 for illumination (based on the design of Hood and Finkelstein, 1986).

Under mesopic conditions, VA plays a less important role than the ability to recognize weak contrast changes. However, there had been no standard CS 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 both time and luminance changed. Despite utilizing a specialized visual performance measurement technique, they did use the widely accepted ‘logarithm of the minimum angle of resolution’ (logMAR) system to classify the level or degree of visual performance. For the purpose of utilizing a uniform terminology within this manuscript, the term “Visual Acuity” (VA) has been limited to describe spatial resolution under photopic conditions. The term “Contrast Sensitivity” (CS) has traditionally been used to describe the ability to distinguish small differences in contrast under conditions involving decreasing luminance. The term “Contrast Acuity” (CA) is being applied to describe the combined ability of spatial resolution, under the combined conditions of both decreased luminance combined with conditions of decremented contrast. Visual acuity is normally recorded as a ratio (e.g., 20/20 in the Imperial System of using feet as a reference unit, or 6/6 in the Metric System using meters as a reference unit), while CA is able to make use of the logMAR format of recording letter chart responses in relation to changes in size and contrast within a sequentially decreasing visibility system (i.e., smaller details, under increasingly obscured conditions).

The vast majority of past mesopic visual performance studies were predominantly isolated to evaluations of various eye disease conditions (e.g., dry eyes, mild cataractous conditions, Stevens-Johnson Syndrome) using CS alone as the performance index. More commonly, it has been noted by a number of investigators that after corneal refractive surgery, any number of patients with excellent vision during the day tended to experience a disturbance in their night vision, such as decreased CS. This CS decrement was presumably due to increased wavefront aberrations associated with, or resulting from either corneal distortions, or from night-associated pupillary dilation exceeding the normal surgical refractive zone of 6 mm in diameter. For this reason, Hiraoki felt that corneal laser refractive surgery may become an important public health issue in the future (an issue this author agrees with for entirely different reasons). Puell, Palomo, Sanchez-Ramos, and Villeno (2004), prior to the Hiraoki study, obtained normative photopic and mesopic Pelli-Robson CS data for age-specific subject samples (ranging in age from their 20s through their 70s). However, there were no scotopic CA data available for larger population comparisons until February 2016 (Bartholomew, Lad, Cao, Bach, & Cirulli, 2016) in which data were obtained on 504 subjects averaging 22.8 years of age. While the Puell subjects ranged in age from youthful to elderly status, all of the 504 Bartholomew subjects were university students, thus failing to account for all possible age groups. The remaining studies of note excluded scotopic CA data, using only relatively young subjects, as well. The Hiraoki et al. study used 68 normal subjects, averaging 24.03 years of age, while a Lattimore and Cornum study (1992) used 223 normal aviation subjects over multiple visits, with an average age of 26.40 years, followed by Barrio, Antona, and Puell (2015) using 47 subjects averaging 22.9 years of age.

Approaches Regarding a Mesopic Sensitivity Standard

As touched on previously, Puell et al. (2004) described Pelli-Robson CA under photopic and mesopic luminance conditions in a large Spanish population over a wide age range in an attempt to provide initial normative values. A further aim was to compare the effects of age on photopic VA, and on photopic CS; similarly, Puell sought age-based differences in mesopic VA and on mesopic CS. With those goals in mind, they conducted a cross-sectional study of 292 participants, stratified by age, divided into six groups. Binocular CS was determined with best spectacle correction using the Pelli-Robson letter chart at a 1 meter (m) test distance under photopic (85 cd/m^2) and mesopic (0.15 cd/m^2) luminance conditions. Bario et al. (2006) explored the effects of contrast reduction on younger and older adults' reading behavior and examined whether readers rely on word predictability to compensate for poor contrast. Given that poor contrast can degrade text and may influence reading behavior, readers may compensate for visual degradation of text by taking advantage of word predictability. Older adults, in one test, read sentences presented with 10 levels of contrast. While younger adults read high-, medium-, and low-contrast sentences that varied in target word predictability (high vs. low). Over the years, a number of visual performance studies had separately evaluated the effects of varied luminance on acuity, as well as the effects of varied target contrast on acuity. It wasn't until approximately the early 2000s, when a great many refractive surgery post-operative assessments began studying visual performance under varied luminance and contrast levels, that interest in visual performance under degraded conditions began to increase.

Despite a decade and a half of government-voiced interest in visual performance under degraded conditions, current knowledge has been unable to establish validity regarding either of the following conditional challenges:

a) either both visual contrast- and resolution-sensitivity are completely independent of one another, exhibiting no evidence of interaction, or
b) both aspects of visual performance involve interactive inhibition and/or interactive summation at varying performance levels, depending upon the specific operant conditions present.

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 these unknown determinants or controlling factors must be understood, before a complete valuation of mesopic visual performance standards are to be derived. Puell et al. have provided normative photopic Pelli-Robson CS data for isolated, specific populations. However, there are no mesopic CA data available for large-sized, general populations, especially taking into account all possible ages, genders, and genetically specified backgrounds. Because visual disturbances at night are symbolic of overall visual function, the lack of a critical mass of mesopic-based performance, serves to inhibit any attempt at conducting a classic meta-analysis, which represents a significant gap in the vision-science literature. Johnson and Casson (1995) noted that although previous investigations have reported that changes in background luminance, stimulus contrast, and dioptric blur can each affect CA 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 DVEs characterized by a combination of low background lighting with decreased contrast.

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 tool capable of easy application within the realm of an aviation medicine-based eyecare clinic. The SLCT is now available as a mobile tablet software 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:

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

There are several other CA tests which probe larger-sized letters than the ten-letter per line, 20/25 sized letters of the SLCT. The Pelli-Robson test uses five 20/40-sized letters (Rabin has since adapted that strategy), organized on a logarithmic contrast scale much like the Rabin SLCT. This larger test letter size permits analytical probing into the mid-level, ‘peak’ aspects of the CS curve, providing completely different information on the visual system’s functions than the SLCT provides; this system may have separate charts using different levels of decreased or low-contrast across each chart, or sequentially decreasing contrast on the one chart, similar to the SLCT.

Contrast sensitivity is 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 the two become indistinguishable from one another is another means of describing CS. Contrast sensitivity is a function of the size (coarseness/fineness) of image features, which approximates the equivalent spatial frequency. Figure 2a shows how the SLCT utilizes 20/25-sized letters, arrayed in 14 lines, possessing 10 letters per line. The top line utilizes a log to the base 10 contrast value of 0.0 (or maximum contrast of black on a white background). Each succeeding line (going downward) exhibits a 0.1 Log unit reduction in contrast. This design permits visual performance analysis on a continuous scale (as opposed to the standard Snellen discreet resolution scale), enabling the use of parametric means of statistical analysis. Figure 2b displays Rabin CA using the Pelli-Robson style. The five-letter, 20/40 size stimulus strategy on the right follows a strategy developed as the Pelli-Robson Chart, which assesses the peak aspect of the CS curve, while the 10-letter 20/25 sized chart probes the far end seeking to document the minimum size of visual stimulus that is clearly resolved.

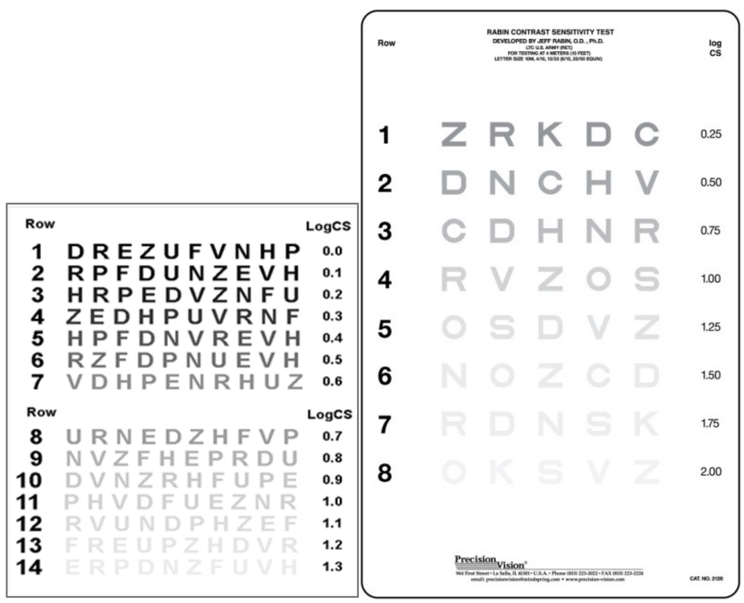

Figure 2. *(a)* Rabin SLCT using 10, 20/25-sized lettering. *(b)* Rabin CA using the Pelli-Robson style.

The test image shown in Figure 3b was first produced by Campbell and Robson (1968) to illustrate the form of the function in a very intuitive manner: using one’s own visual system, without time-consuming measurements. Referring to the graphs in Figure 3, “the pixel luminance is modulated sinusoidally along the horizontal dimension. The frequency of modulation (spatial frequency) increases logarithmically (i.e., with exponential increase in frequency from left to right)." (Campbell & Robson, 1968). The contrast also varies logarithmically from 100% to about 0.5% going from bottom to top, or whatever a computer monitor's 8-bit gray scale display is able to provide. The luminance of peaks and troughs remains constant along a given horizontal path through the image. Therefore, if the detection of contrast is dictated solely by image contrast, the alternating bright and dark bars should appear to have equal height everywhere in the image. However, the bars appear taller in the middle of the image than at the sides. This inverted U-shaped envelope of visibility is the CS function. The exact location of the peak depends on the viewing distance. Try moving farther away from the display, and back closer. Note that the apparent position of the peak shifts as you do this.

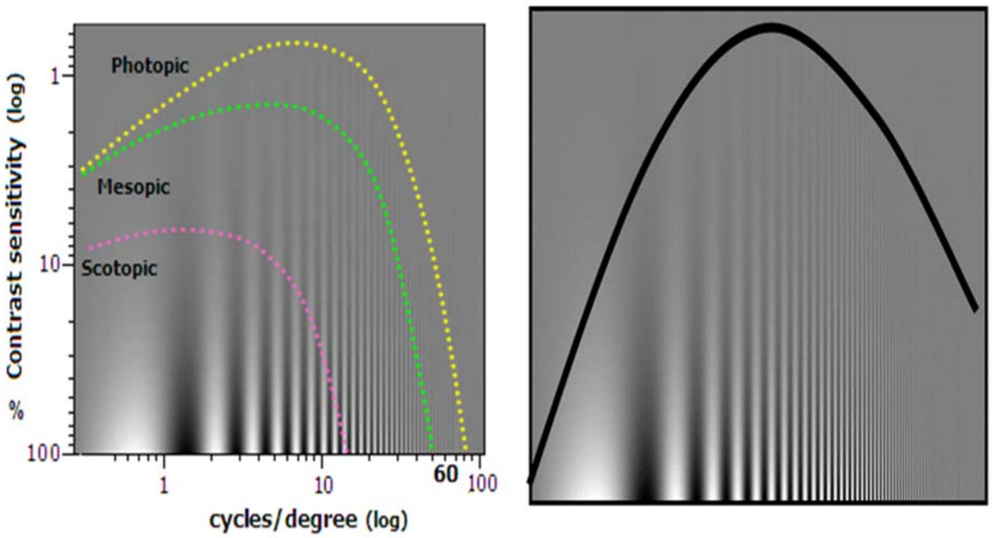

Figure 3. *(a)* Ocular Contrast Sensitivy Curves. *(b)* Campbell-Robson Contrast Sensitivity Curve.

Therefore, the inverted U-shaped envelope is not in the image, but reflects the property of one's specific visual system. In general, recent investigators, after reviewing their own data, as well as that of others, have concluded that factors other than refraction are of primary influence in CA under mesopic, low-contrast/low-luminance conditions. A narrow mesopic range of luminance is characterized by concurrent rod and cone function, which could theoretically occur in-concert, which is not necessarily the norm. Dynamic evaluation conditions will reveal real-world visual performance abilities via specific photoreceptor functions. Static evaluation conditions may provide greater functional detail, but would fail to provide an essential understanding of how the two photoreceptor systems could work together, despite their inherent processing and timing inequities. Combined, organized basic and applied research addressing a further understanding of this quasi-joint realm of conflicting photoreceptor functions (i.e., mesopic conditions) are critical to understanding important DVE performance characteristics and critical visual thresholds.

Snellen Acuity Chart

Figure 4 is a representation of a Snellen Acuity Chart. Despite being the most widely used chart for VA testing, there are numerous limitations characteristic to these standard acuity measurements when using the current Snellen distance acuity chart.

- The different numbers of optotypes per row: as a result, the difficulty of the task increases as the optotypes become smaller.
- The irregular progression in letter size; the scale of the measure is not the same over the entire extension of the chart, so that the gain or loss of one line does not have the same value in different parts of the chart.
- The differences in the recognition difficulty of the optotypes; the chart includes both relatively easy letters such as A and L, and more difficult ones such as B, E, and F.
- The difference in background luminance related to different chart manufacturers. The Snellen chart, in spite of its diffusion or widely distributed clinical use, presents too many flaws to be used as a reference standard.

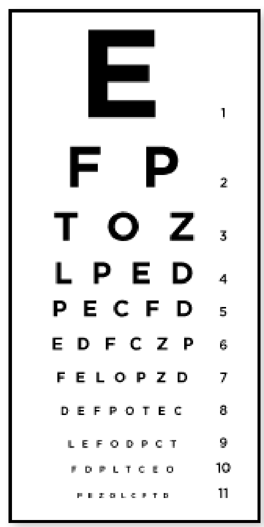

Figure 4. Snellen Acuity Chart.

Charts with a regular progression of optotype size and spacing, with the same number of letters per row, using letters of approximately an equal level of recognition-difficulty (e.g., Landolt C or Sloan letters), are more useful for standardization requirements (e.g., the Early Treatment Diabetic Retinopathy Study Chart [EDTRS]). Visual acuity testing is currently employed for different purposes, ranging from the assessment of refraction to the evaluation of visual function. Wong and Kaye (1989) suggested that different charts may be useful in relation to specific needs, and each chart should balance sensitivity, specificity, and the desired duration of examination time. Highly sensitive test charts produce a low percentage of false negatives, while highly specific tests produce few false positive responses. The sensitivity of any chart is related both to the number of letters per row and the requested number of correct identifications for VA threshold assessment. The specificity of the test may be reduced by difficult and time-consuming examinations. A two-letter chart combined with a suprathreshold end point may be useful in VA screening.

Figure 5. The Early Treatment Diabetic Retinopathy Study Chart (ETDRS). Large epidemiological population studies may benefit from more balanced tests such as the ETDRS five-letter chart.

Minimum Angle of Resolution (M.A.R.)

The VA threshold may be expressed in terms of the minimum angle of resolution of the acuity chart's optotype letter tested. The advantages of this kind of format include:

- It states the VA in absolute terms.
- It does not involve any assumption of normal reference values.
- It can be used with charts of any letter-size progression.
- It allows direct comparison of values obtained with different distance charts.
- It allows direct comparison between distance- and near-acuity levels.
- It allows easy conversion from and to the Snellen notation.
- It is expressed as an internationally used unit of measurement and is therefore useful in defining an international standard.

The Logarithm of the Minimum Angle of Resolution (logMAR)

The LogMAR is the common logarithm of the minimum angle of resolution, permitting a fast and easy VA specification. This notation has further advantages in comparison to the MAR notation, such as:

- Easy progression in steps of 0.1, from +1 to -0.1; and
- The ability to express VA as a continuous variable for the purpose of continuous parametric statistical analysis.

Lasagno, Issolio, Pattimi, & Colombo (2014) reviewed transitional spaces from exterior to interior as functional vision barriers in ageing. A subject moving from a brighter exterior into a dimmer interior faces an abrupt change in the level of lighting. Aged individuals, when confronted with this potential functional barrier to optimal visual performance, were likely to be the most adversely affected.

Military-Specific Relevance

A series of independent technological advances have had a major impact upon Army Aviation in general. While modern methods of providing visual information via electro-optics / visionics systems have extended the aviation operational envelope, these devices are becoming increasingly incompatible with spectacle wear. Furthermore, flat-panel displays, backlit by white or colored light emitting diodes (LEDs) are becoming an additional means of complicating the visual performance demands placed upon our nation's Soldiers and military aviators, who now are challenged by small print, varied lighting conditions, fatigue, as well as ill-defined compensatory challenges. Currently available military clinical programs using refractive surgery procedures use Photorefractive Keratectomy (PRK) and Laser-Assisted in-Situ Keratomileusis (LASIK) as the two most commonly approved procedures for Army Aviators and Special Operations soldiers.

Military operations in the Iraq and the Afghanistan theaters have highlighted flight operational activities within DVEs as presenting a significant risk to safe helicopter operations. 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 is termed brownout or whiteout, depending on the environment. A DVE can also be caused by clouds, haze, and moonless/starless nights. A DVE causes a loss of spatial orientation and situational awareness, which has on several occasions led to controlled flight into terrain (CFIT) and ground obstacle collisions, accompanied by the loss of aircraft and personnel. Degraded visual environments (which are directly comprised of low-luminance and low-contrast visual challenges) has subsumed a major cost to the Army in the last 10+ years of combat experience flying in Irag and Afghanistan. Operational flights under brownout conditions have cost the Army numerous rated aviator lives, as well as a huge financial burden in rotary-wing aircraft damage, resulting from approximately 800 Class A accidents over the 8-year period of 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) number one priority. While these U.S. Army Research, Development and Engineering Command (USARDEC) -developed technological countermeasures to DVE have the goal of making landing, navigating, and fighting easier, the countermeasures themselves may 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 Operation Iragi Freedom (OIF) and Operation Enduring Freedom (OEF) were due to noncombat factors, including the presence of a DVE (CONOPS for Aircraft Operations in DVE, 4 April 2011, USAACE CRD). More than a third of all helicopters lost in Iraq and Afghanistan have crashed because of brownout or CFIT. 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 $1 billion.

U.S. Army Aeromedical Research Laboratory investigators are involved in five major Research, Development, Test, and Engineering (RDT&E) efforts, which are predominantly extramurally funded by a variety of Army engineering laboratories (McAtee et al., 2016). However, some aspects of USAARL medical research are core-funded by the Military

Operational Medicine Research Program (MOMRP). All MOMRP-funded research activities are focused on achieving a greater understanding of DVE-associated vulnerabilities, as well as determining the best means of mitigating the disastrous effects associated with attempting to conduct military aviation operations under these debilitating visual conditions. Human “visual performance characterization” is a goal published within the Training and Doctrine Command’s (TRADOC’s) Human Dimension White Paper, published in 2009, which opens up the medical research community’s access to potential human dimension-based grant funding. This atypical, abbreviated assessment of visual resolution limits, analyzing two related datasets, could be construed as a “high-risk/high-payoff” topic. In reviewing these limits of human unaided visual resolution under conditions of DVE were initiated in hopes of spurring a more advanced research task area evaluating DVE flight, its challenges, and identification of the means to overcome these disastrous effects articulated at the beginning of the military-specific relevance section. As was discussed in the very first paragraph of this background review, 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 SouthWest Asian desert climates). The “chamal” winds, illustrated by the three photos in Figure 6 at the top of the next page, taken when deployed to Iraq can prove to be extremely disorienting. Any attempt at ground mobility, either in foot or in a vehicle, would be met with extreme uncertainty as to finding the safe way ahead. Any attempt at rotary-wing flight under these conditions would be fatal. However, the low-level flight of a helicopter itself can induce a debilitating degree of sand downwash, preventing normal VA while so exposed (see last photo below); 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 (NVGs) 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 CS. However, there are no generally standardized CS scales in normal persons in the mesopic range, including Army aviation personnel.

Figure 6. Demonstration images of the “chamal winds” typical to SouthWest Asia. The photos were taken at varies offset ranges, enabling the reader to gain a subjective assessment of its effects on visual performance.

Army Regulation (AR) 40-501 has established medically based vision performance standards for accession, as well as for retention. Historically, research into the enhancement of natural abilities has received little support or attention within the Army Medical RDT&E realm. However, the advent of TRADOC’s Human Dimension initiative (based on their similarly named white paper) has provided some programmatic encouragement to medical research personnel with past experience in vision performance enhancement research. Traditionally, students enrolling in military specialty schools (e.g., airborne, Ranger, special forces, flight, aerospace training) have had to meet stringent vision standards for acceptance into those training programs. Over the years some standards have been subject to waiver, the requirement for relative emmetropia being one of them. This, in conjunction with changes in related standards, and with the development of late-onset maturational myopia in some individuals, has presumably led to the development of a sizeable ametropic subset within the Army aviation community. Due to the advent of the routine application of laser refractive surgery or refractive error correction, there are no currently available numbers of Army aviators accessed with an inherent refractive error (usually myopia); nor have there been any data available to determine the relative percentage of current spectacle wearers, current contact lens wearers, and current recipients of refractive surgery. In the early 1990s, over 23% of Army aviators (Schrimsher & Lattimore, 1991; Lattimore & Schrimsher, 1993) were ametropic (or spectacle-wearing), and 27% of Air Force aviators (Baldwin et al., 1999) were similarly ametropic. It is therefore reasonable to expect Navy and Marine Corps percentages to be far less, given that they do not allow Service Members with high refractive errors to pilot aircraft equipped with these advanced visionics systems.

Established Army standards have varied little from the initial days of aviation's nominal birth in the early 1920s. Among a number of visual requirements, prospective aviators had to meet rigorous Snellen VA requirements, a high- 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 VA 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 VA, stereoscopic ability, and color sensitivity receiving the greatest amount of emphasis (and the least degree of leeway of flexibility) in terms of medical examination standards.

Safety of flight has always served as the strongest incentive to the strict monitoring of VA (among all the other vision performance standards) throughout the course of an aviator's career. High-contrast Snellen VA has served as the standard screening tool for the appraisal of visual function; 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). It is still the standard for clinical visual assessment for ocular examination across all classes of patient care, unchanged from the days of its initial development by Helmholtz (working under the Austro-Hungarian Empire in the 1880s).

Despite the persistent application of Snellen VA under all these clinical circumstances, a number of investigators have sought to develop a more sensitive means of assessing visual resolution performance (Lovie-Kitchin & Brown, 1986; Rabin, 1996). In support of all the visual performance testing paradigms, CS 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 CS testing under cycloplegic conditions had been proposed as a critical visual assessment task integral to the Army's Class 1 Flight Physical (Ginsburg, 1981 and 1984; Bachman & Behar, 1986). During a Class 1 flight physical, a topically applied 1% cyclopentolate solution serves to artificially induce paralysis of the ciliary muscle of the eye. The topical cycloplegic pharmaceutical primarily inhibits accommodation; a secondary effect is pupillary dilation (which includes spherical aberration). Initial Small Letter Contrast Test (SLCT) research has shown the test's sensitivity to be more discriminating than traditional VA testing. It is also more responsive: to small amounts of blur, to subtle changes in the luminance of the stimulus, to vision with two eyes compared to one eye, and for identifying visual differences among pilot trainees (Rabin, 1994 and 1996). The goal of this preliminary research is to use this tool as a means of quantifying the degree of spherical aberration within eyes subject to cycloplegia, as the initial or most basic of such visual aberrations.

Visual acuity has been proven to be poor under combined low-contrast/low-luminance conditions, but the effects of altered oxygenation states on low-contrast acuity under conditions of dim luminance are not well documented at all. However, Connolly and Barbour examined the normobaric contrast acuity thresholds (CAT) of 12 healthy volunteers at low photopic (12 cd/m^2), upper mesopic (1 cd/m^2), and mid-mesopic (0.1 cd/m^2) luminance conditions while under varied oxygenated conditions (14.1% O_2, 100% O_2, and 21% O_2) (2009). Relative to performance under mild hypoxia at 3048 m (10,000 ft), supplementary oxygen can extend functionally useful vision to even lower light levels. These findings are directly relevant to contemporary military rotary-wing night flying, when viewing the external scene directly, or through night vision devices, or directly viewing a dimly illuminated flight deck, validating the need for O_2 availability in every aircraft, regardless of its anticipated altitudinal flight plan. This is absolutely critical for Army aircrew currently operating in and around Afghanistan, Columbia, and Peru.

Operational studies have indicated the presence of superior, average, and poor visual performers, with respect to target detection, target recognition, and target identification. However, no screening tests have been established and standardized that are capable of consistently differentiating between the groups of operational visual performers. Without paired acuity and 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 on their first day of reporting for entrance into flight school, does evidence merit in support of further detailed study of those individuals. Past internal comparisons of VA in military personnel using either Snellen or low-contrast/low-luminance methods were not influenced by type of contact lens worn, by the use of spectacles, by age, or over 2 years' time between entrance and exit assessments. One's base ability level remained relatively stable across all those varied conditions. External comparisons of the two acuity methods 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 the military specialty schools (e.g., airborne, Ranger, special operations), will need to be changed. These referenced test data represented a subset of an applied contact lens study completed a number of years ago. There most assuredly are computer display-based contrast threshold systems that could be employed on a much larger subject sample.

The operational flight-oriented visual deficiency phenomenon, labeled as a DVE, has seen at least a half-dozen physical solutions seeking to aid the identified contrast resolution deficiency. Despite the growing emphasis by TRADOC on the "Human Dimension," there are no other efforts oriented toward analyzing the natural ability of human unaided vision to perform at the highest levels of sensitivity, or even well beyond the expected ranges. Does that overarching effect on individual sensory thresholds hold for sensorimotor activities? Will individuals with exceptional vision, when under conditions of low contrast and low luminance, perform sensorimotor tasks in an exceptional manner? A number of theories regarding the underlying cause of mesopic CA resolution variation are under continued assessment and review. Certainly each factor could partially contribute to reduced visual resolution under mesopic conditions (assuming we all hold the potential for exceptional mesopic CA, while some are consistently affected negatively by a number of factors yet to be validated). Alternatively, each could play a varying role, dependent upon the specific conditions encountered, and the demands made upon the visual system. Alternatively, all these issues are subordinate to the overarching influences of fatigue or old age.

Methods

This research goal was to review any and all studies on visual performance under either, or both, of these two conditional variables (i.e., decreased target contrast in conjunction with conditions of decreased luminance, as well as each individual condition). Certain vision data, which represent a subset of a large contact-lens-related study, completed over 30 years ago, were utilized as one of the deidentified visual performance assessments considered for the meta-analysis. This is particularly so, given the Defense Health Agency's (DHA's) emphasis on the development of vision standards (to include specific standardized tests) which will validate each of the specifically selected systems. Meta-analysis has been defined as the statistical analysis of a collection of analytical results for the purpose of integrating the findings. Systematic reviews or meta-analyses of randomized controlled trials (RCTs) and evidence-based clinical practice guidelines are considered to be the strongest level of evidence upon which to guide practice decisions (Guyatt, Rennie, Meade, & Cook, 2002). Combining the findings across a number of similar studies represents an attractive alternative to strengthen the evidence for individual variability in one's tolerance to decreasing illuminance in combination with decreasing image or target contrast. Yet, a systematic review of a number of studies addressing a common question will inevitably bring together material with an element or degree of diversity. Such studies will differ in design and conduct, as well as in participants, interventions, exposures or outcomes studied. Such diversity is commonly referred to as methodological heterogeneity, which can help explain observed discrepancies in the contrasted and compared results of the studies. Statistical heterogeneity exists when the true defects being evaluated differ between studies. Because of differing sample sizes, and subject populations, each study included within this review and statistical comparison has a different level of sampling error. Thus, one problem in combining studies for integrative purposes is the assignment of weights that reflect the relative "value" of the information provided in a study. It is therefore important to be able to quantify the extent of heterogeneity among a collection of studies.

The selected means of considering heterogeneity in this study is an estimation of each cross-study variance of the specific parameter of interest (in this case, the range of tolerance to decreasing contrast, as well as the range of tolerance to decreasing target illuminance). This means of heterogeneity determination has been labeled as a “random-effects meta-analysis” or alternatively, a “quasi, meta-analysis.” Since there are only a few published studies that can be included in this specific combined meta-analytical comparison, the effective power may be considered to be relatively low. However, key aspects of each of these specific-comparison evaluations have been shown to be predictably reliable with little variability, enabling elevation of the effective power to be considerably higher than would normally be encountered.

A complete review of eligible published studies was performed, determining the study parameter heterogeneity, including a range-determination delineation. A combined analytical review of the existing literature resulted in a data distribution estimate. These data will later feed into a planned analysis and manuscript regarding the effectiveness of current Army vision standards (which are restricted to photopic conditions), with a conclusively established judgment regarding the acceptability of the existing standards, as well as the provision of a concerted recommendation regarding an updated change with regard to a series of vision testing standards. The goal in this next manuscript will be to delineate a suite of formally modernized vision testing standards (i.e., MRMC Protocol 18880). The acuity data, which is recorded in a logMAR format, will be documented as continuous variable outcomes within an Excel Workbook data sheet. Heterogeneity between the results of each different type of study was examined in order to indicate statistically significant heterogeneity, to include the stability and reliability of the results. Last of all, publication bias was a self-assessed critique, if at all applicable. The PI’s own induction tendency toward verification bias concerning previous original research findings prompted inclusion of a self-enforcement co-investigator assessment.

Of the key studies previously identified within the introduction section (i.e., Hiraoki et al., 2015; Bartholomew et al., 2016; Lattimore & Cornum, 1992; Bario et al., 2015; and Puell et al., 2004), none have provided a complete comparative and contrasting assessment of visual performance at all three major categories of illumination (photopic, mesopic, and scotopic conditions). Furthermore, none have utilized the same measure of visual performance, varying by the application of 5 different visual performance testing systems (i.e., FVA measurement system (AS-28; Kowa); Freiburg VA; Bailey-Lovie test under 8% contrast; EDTRS; and Pelli-Robson letter chart). Subject test populations also varied by test distance, subject age, number of subjects, level of luminance utilized, and target contrast. Referring to Table 1, presented in the Appendix due to its landscape orientation, it is clear that a traditional meta-analysis is simply not appropriate due to the complexity of variable discord. However, specific heterogeneity assessments can be accomplished regarding the few areas of variable conformity, which is equivalent to the prior identification of a “random-effects meta-analysis” or alternatively, a “quasi, meta-analysis,” explaining the inclusion of that terminology in the titled manuscript heading.

Results

The analytical results were widely varied based on differing test conditions, subject ages, both degree and general category of the responses, and their resultant conclusions. Thus a review chart has been prepared delineating each of the varied studies, and their individual categorizations. This data review, and specific heterogeneity assessment was accomplished by specifically assessing the mean visual performance data of each identified study with regard to the utility of its application to the DVE challenge in military aviation.

Hiraoki et al. (2015) demonstrated that visual function measures all deteriorated in mesopic conditions compared to photopic conditions, even after a 15 minute (min) dark-adaptation period. Their results were in agreement with the study by Johnson (1976), who measured VA under several different low-light levels using sinusoidal gratings. Even with correction in-place for night myopia, VA was significantly decreased under the mesopic condition than under photopic conditions. This result strongly suggests that factors other than refraction influence VA under low light conditions. It has been suggested that decreases in VA occur at lower light levels because of neural factors associated with decreasing retinal illuminance, and not optical blur from the established myopic shift (Johnson, 1976; Arumi, Chauhan, & Charman, 1997). Hiraoki et al. (2015) concluded that their own results further support the neural factors concept.

Puell et al. (2004) described Pelli-Robson CS under photopic and mesopic luminance conditions in a large Spanish population over a wide range of age groups in an attempt to provide normal values. A further aim was to compare the effects of photopic VA on photopic CS and on mesopic CS, using a cross-sectional study of 292 participants from Spain, stratified by age into six groups. Photopic letter CS began to decrease gradually from the 61- to 70-year-old age group onward, Bartholomew et al. (2016) found their scotopic VA population passed Shapiro-Wilkes test ($p > 0.001$) for normal distribution. The scotopic CS population did not pass Shapiro-Wilkes test ($p < 0.001$), due to a tail of low performers. Scores were normally distributed when restricting the data set only to those who performed no more than 2 standard deviations (SD) below the mean (N=25). This restriction had no significant impact on their predicted stepwise model, so they retained these 25 individuals in the final overall analysis. In reviewing the combined 1992 USAARL CA data (above), it is easy to see the mesopic acuity data are essentially normal in appearance and similar to Bartholomew with the extreme data points tailing off in a skewed aspect. The USAARL scotopic acuity data varied between 0.10 and 0.80, while the Bartholomew data ranged between logMAR 0.08 and logMAR 1.22, with the Bartholomew data possessing a wider skew in the poorer CA direction. The USAARL mean has been determined to be logMAR 0.40 (the peak distribution), while the Bartholomew mean was determined to be logMAR 0.71, a somewhat wider distribution range. Given that Bartholomew worked with a large number of volunteer subjects (504), which extended a wide range of ages (enough to make age-based CA decisions), it is understandable that their low-end CA performance would be wider-ranging than the USAARL data, which utilized research subjects ranging from their early-20s in age to their mid-40s in age. Understanding the two distribution patterns differ by an induced age-based component enables the observer to see the close similarity of both distributions. In his conclusion, Bartholomew et al. concludes that by focusing just on young individuals with excellent photopic vision (similar to rater aviators), they found a wide variation in performance that is largely unexplained by a range of factors, such as Circadian preference, photopic visual performance, intelligence, or eye characteristics. Combined with high test-retest agreement and the existence of diseases uniquely targeting rod systems, their findings argue for a strong genetic component of healthy variation in night vision that they believe requires closer exploration. Coincidentally, in a separate USAARL study on urban combat issues, facility of dark adaptation data were obtained from young (age 19–25) volunteer research subjects, which were compared to the response characteristics of these CA data distributions. Incredibly the two distribution patterns were so parallel as to be very much alike in their specific range characteristics, as well as in their mean data distribution (Lattimore & McAtee, 2017). The reduction in mean CS between the oldest and the youngest age groups was 0.20 log units under photopic conditions, and 0.33 log units under mesopic conditions, from the 51- to 60-yeaer-old age group onward. Both photopic and mesopic letter CS significantly improved as photopic VA increased. Under mesopic conditions, Pelli-Robson CS began to decline one decade earlier than under photopic conditions and was affected by VA. Normal values for mesopic CS could be of help in deciding whether mesopic function is normal, or if a decrease in CS is pathologic in nature.

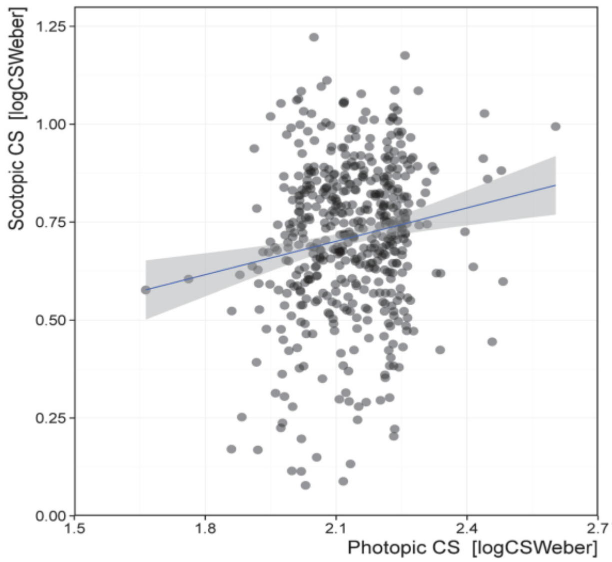

Figure 7. Correlation between scotopic CS and photopic CS. Visual acuity in logMAR units have an inverted scale, meaning that better performance is shown here with a higher score. Photopic CS explained only 2.5% of the variance in scotopic CS.

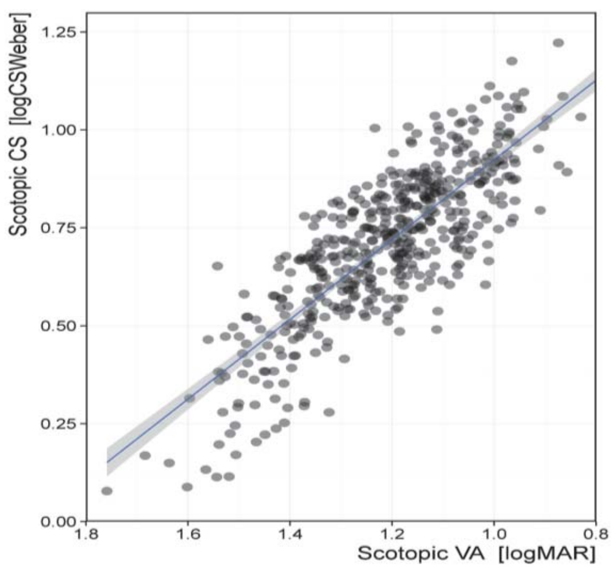

Figure 8. Correlation between scotopic CS as a function of scotopic VA. Visual acuity in logMAR units have an inverted scale, meaning that better performance is shown here with a higher score. Scotopic VA explained 67.1% of the variance in scotopic CS.

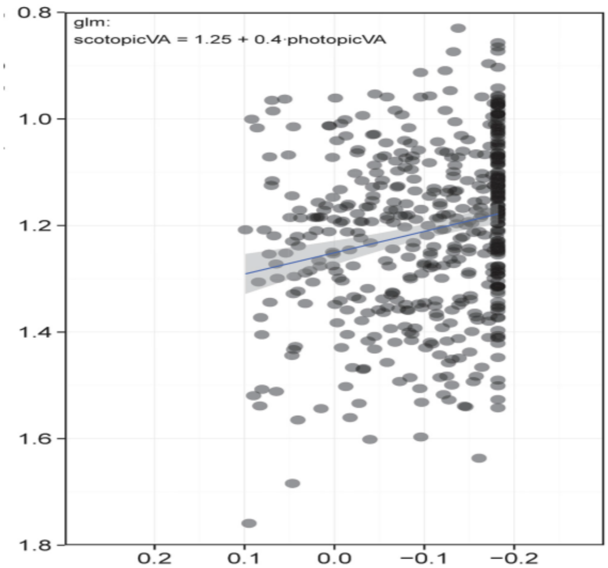

Figure 9. Correlation between scotopic VA as a function of photopic VA. Visual acuity in logMAR units have an inverted scale, and CS is in logCSWeber units, meaning that better performance corresponds to the top right. Photopic VA explained 4.1% of the variance in scotopic VA.

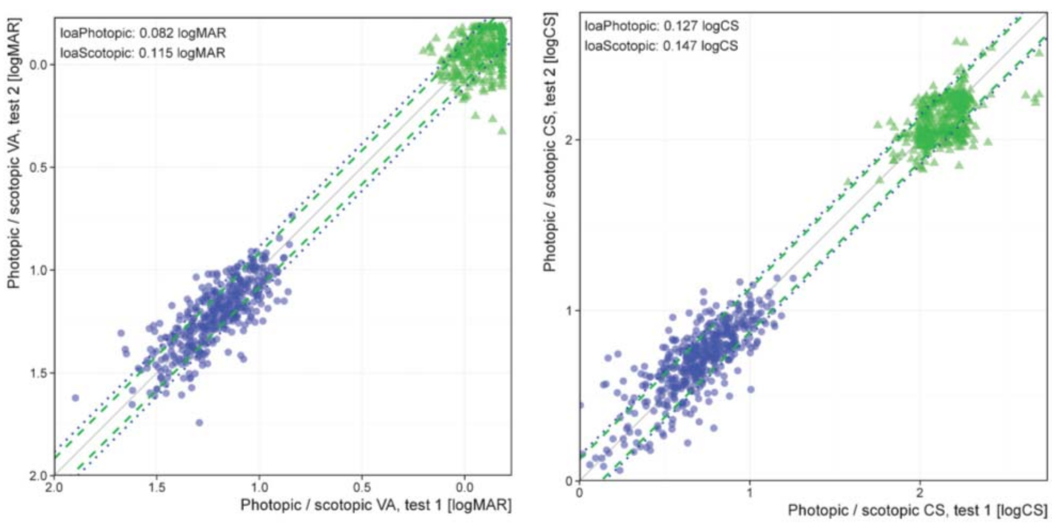

Figure 10. *(a)*Test-retest assessment: visual acuity. *(b)* Test-retest assessment: contrast sensitivity. The green triangles near the top right of the graphs represent photopic luminance; the blue discs near the bottom left of the graphs represent scotopic luminance.

Result of the first test on the abscissa, second test on the ordinate. Grey 45°- line is the identity line, next to it the ± limits of agreement (photopic, dashed; scotopic, dotted). Visual acuity in logMAR units have an inverted scale, and CS is in log CS Weber units, meaning that better performance corresponds to the top right for both graphs. Photopic measures of VA or CS are markedly better than scotopic ones. The 95% limits of agreement are remarkably similar. All in all, there is no marked deviation from a normal distribution, and the reliability is good for the range measured.

Human CA Variability: Increased CA variability, along with decreased CA, result from decreased background luminance and decreased test letter contrast.

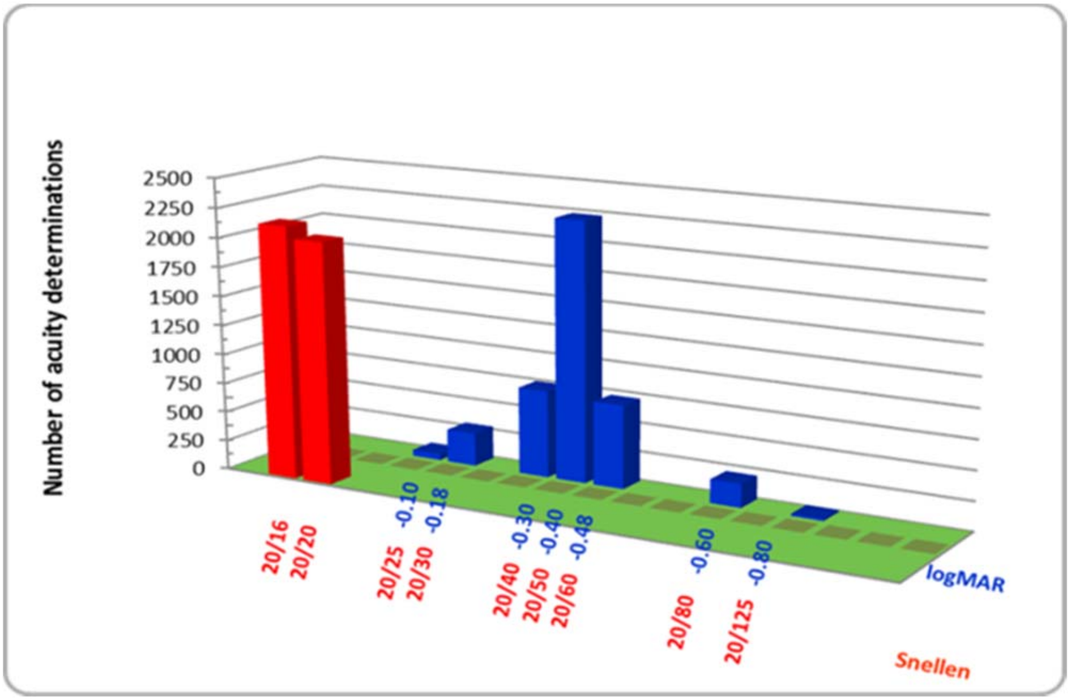

Figure 11. Test chart at 8% contrast, with low-luminance conditions. The red columns are representative of suprathreshold Snellen Acuity, while the blue columns are representative of the mesopic CA performance for the same grouped individuals. This previous Research, Development, Test and Evaluation (RDT&E) effort was aligned toward demonstrating varied visual performance tolerance to visual resolution stressors while using soft, extended-wear contact lenses. There were 223 subjects following a monthly and quarterly follow-up examination schedule for 2 years, yielding approximately 8500 data points, normally distributed from logMAR -0.10 to logMAR -0.80 (see above). The distribution of these data parameters closely agree with Bartholomew et al., who found separate normal distribution patterns around logMAR CAs of -0.18 under mesopic conditions, and a mean logMAR CA peak of 1.19 under scotopic conditions.

Bario et al. (2006) explored the effects of contrast reduction on younger and older adults' reading behavior and examined whether readers rely on word predictability to compensate for poor contrast. Given that poor contrast can degrade text and may influence reading behavior, readers may compensate for visual degradation of text by taking advantage of word predictability. Older adults, in one test, read sentences presented with 10 levels of contrast. While younger adults read high-, medium-, and low-contrast sentences that varied in target word predictability (high vs. low). The results revealed older adults' reading rates were slowed to a greater degree by low contrast; comprehension was less influenced by contrast. Older adults read high-predictability words faster and comprehended them better than low-predictability words, significantly so for high- and medium-contrast sentences. Younger adults comprehended high-predictability words significantly better than low-predictability words for high- and low-contrast sentences. Consequently, it was determined that low contrast was more detrimental for older adults, yet even young adults revealed some adverse effects when contrast was reduced. Highly predictable words benefited older adults by significantly reducing their reading times and benefited all readers by significantly increasing their comprehension. A host of visual performance studies have separately evaluated the effects of varied levels of luminance on acuity, as well as the effects of varied-target contrast on acuity. Under mesopic conditions, Puell et al. (2004) found Pelli-Robson CS began to decline one decade earlier than under photopic conditions, and was affected by VA (when VA normally plays a less important role than the ability to recognize weak contrasts). Expectations of normal CA value ranges for mesopic contrast conditions could be of help in deciding whether one's level of mesopic function is normal or not. Doshi, Sarver, & Applegate (2001) found that under low-contrast conditions the Indiana Eye visual performance model yielded VA determinations that were significantly closer to those of real eyes ($p < 0.0003$), than VA determinations by two other models of visual performance, concluding that visual performance can be simulated by an eye model. The simple single surface Indiana Eye model, with no spherical aberration, best simulated both high- and low-contrast VA. This finding is important with regard to establishing target standards and cutoffs.

Rabin and Wicks (1996) assessed visual performance across both the contrast and the luminance domains, seeking to establish standardized norms separating normal visual performance from distinctly abnormal sensitivity. Their paper on "Measuring Resolution in the Contrast Domain" compares expected responses for Pelli-Robson CA, and for the SLCT, identifying the normal ranges of resolution, separating them from the below normal response range.

TABLE 1. Detecting differences from normal.[a]

Vision Test	Mean ±2 SD[b] (mean Snellen VA)	Below Normal
High contrast VA	−0.11 ± 0.12 (20/16)	20/21 or less
Low contrast VA	0.00 ± 0.14 (20/20)	20/28 or less
Pelli-Robson	1.88 ± 0.17	1.70 or less
SLCT	1.21 ± 0.18	1.02 or less

[a] Normal observers tested monocularly (N = 21, age 23 to 60 years).

[b] Decimal units are logMAR for VA and logCS for Pelli-Robson and SLCT.

Figure 12. Expected responses for Pelli-Robson CA and SLCT. Reprinted from "Measuring Resolution in the Contrast Domain".

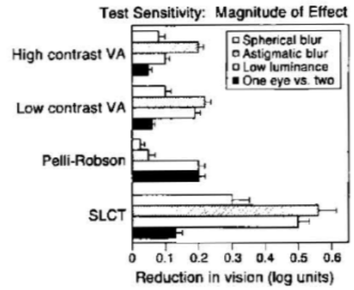

Figure 4. The mean (±1 SE; N = 16 subjects) reduction in vision in response to +0.5 D of spherical blur, +1 D by 90 astigmatic blur, a modest decrease in photopic luminance (from 100 to 6 cd/m²), and vision with one eye vs. two eyes is plotted for each vision test. The reduction in vision was computed by taking the difference between log scores under optimal conditions (best correction; monocular) and test conditions (spherical blur, astigmatic blur, low luminance, or binocular).

Figure 13. The mean reduction in vision from normal subjects tested under conditions of spherical blur, astigmatic blur, low luminance, and one eye vs. two eyes.

Their Figure 4 results (reprinted in Figure 13) from normal subjects (*N* = 16) tested under conditions of spherical blur, astigmatic blur, low luminance, and one eye vs. two eyes. The mean (±1 SE) reduction in vision is plotted in log units for each vision test. For each subject, the reduction in vision was computed by taking the difference between log scores under optimal conditions (best correction; monocular) and test conditions (spherical blur, astigmatic blur, low luminance, or binocular). Figure 13 shows that 0.5 D of spherical blur reduced high and low-contrast VA by only 0.1 log unit (one line of letters), but there was a larger, 0.3 log unit reduction on the SLCT, which was an average of three lines reduction. As shown previously, little change was observed with the Pelli-Robson chart, which uses large letters (low-spatial frequencies) and is thus unaffected by small amounts of blur. A similar, albeit larger, effect was observed with a small amount of astigmatic blur (+ 1 D by 90). There was a 0.2 log unit (2-line) reduction in high- and low-contrast VA, but a greater, 0.55 log unit (5.5-line) reduction on the SLCT. Again, defocus had minimal impact on performance on the Pelli-Robson chart. Although defocus simulates effects of refractive error, a decrease in stimulus luminance can rea because multiple measures were taken within a single session, it is possible that practice or fatigue influenced the results. However, paired t-tests revealed no significant difference between first and final measures of high contrast VA (t = 1.9, p > 0.07). SLCT (t = 1.9, p > 0.08), and Pelli-Robson scores (t = 0, *p* = 1.0), and only a slight improvement (<1 letter) on the second measure of low-contrast VA (t = 2.2, *p* = 0.04 7). Moreover, when the coefficient of repeatability was computed from successive measurements separated by a longer period of time (3 weeks; N = 8 subjects), obtained values were still within one line of letters for high contrast VA (0.09 log units) and for SLCT letters (0.10 log units), indicating that a longer interval between measures does not significantly increase variability. Figure 13 shows that reducing luminance within the photopic range (from 100 cd/m^2 to 6 cd/m^2) produced a 0.1 log (1-line) decrease in high-contrast VA, a 2-line decrease in low-contrast VA, a 1.3-line decrease on the Pelli-Robson chart, but a larger 5-line decrease on the SLCT. As in previous studies, vision with two eyes compared to one eye produced only a slight improvement in high- and low-contrast VA (two letters), but a larger improvement in CS on the SLCT and Pelli-Robson tests (1.3 lines). Results presented thus far suggest that the SLCT is more sensitive than standard letter chart tests to small amounts of blur, modest changes in stimulus luminance, and binocular enhancement.

Rabin and Wick (1996) presented evidence suggesting that the small letter CS is more sensitive than traditional Snellen VA testing 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 VA to spherical and astigmatic blur, low luminance, and vision with two eyes vs. one eye. 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.

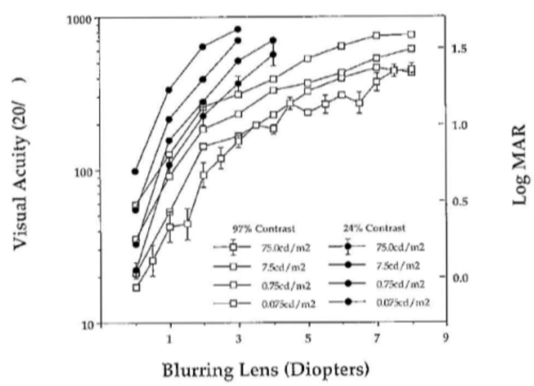

Figure 6. Log visual acuity as a function of dioptric blur for 4 subjects at contrast levels of 97% (□) and 24% (●) at background luminances of 75 cd, 7.5, 0.75, and 0.075 cd/m^2. For clarity, standard error bars are plotted only for the 97 and 24% contrast levels at the highest background luminance.

Figure 14. Log visual acuity as a function of dioptric blur for 4 subjects at contrast levels of 97% and 24%.

Results from studies conducted by Johnson and Casson (1995) demonstrated VA to be significantly affected by all three of the factors they evaluated (background luminance, stimulus contrast, and dioptric blur), and that the effects of all three conditional categories are essentially additive. At all luminance and contrast levels, the reduction in VA was greatest for dioptric blur up to 2.00 D, with a more gradual reduction in VA for dioptric blur of greater than 2.00 D. At all blur and luminance levels, VA decreased gradually for contrast levels down to 20%, and decreased sharply for lower contrast levels. In order to further investigate the above relationships, a series of experiments were then conducted in which measurements of VA were obtained for four subjects, using Landolt C targets of varying contrast, at several background luminances for levels of blur between 0 and 8 diopters. Over the range of background luminances they tested (from 75.0 cd/m^2, down to 0.075 cd/m^2), VA decreased linearly with reductions in luminance.

The additive effects of dioptric blur, contrast, and luminance may provide a basis for predicting VA-related task performance for specific individuals in different visual environments. For example, using Johnson and Casson’s (1995) modeling data, an individual with 20/20 VA under high-luminance, high-contrast conditions will fall to 20/60 acuity, when under low-luminance, high-contrast conditions, and will fall lower still to 20/100 acuity for low-luminance, low-contrast conditions. Similarly, an individual with an uncorrected VA of 6/30 (20/100) under optimal conditions will fall to approximately 6/120 (20/400) under low-luminance conditions and 6/240 (20/800) under low-luminance, low-contrast conditions.

Culham and Kline (2002) documented age-related deficits on photopic (i.e., suprathreshold) visual performance, except with the added variable of induced counterphase flicker, which elicited contrast-, spatial-frequency-, and luminance-based effects, all of which significantly varied as a result of the observer's age. "Considerable evidence indicates that the senescent visual system is compromised in its ability to track temporal change and to resolve spatial detail in temporally modulated target stimuli (e.g., Kline, 1991; Kline & Scialfa, 1996; Owsley & Sloane, 1990; Spear, 1993). "Although optical and sensori-neural factors both appear to contribute to this loss, there is little consensus regarding their relative importance. Nor is it clear if the factors that limit spatio-temporal resolution at threshold contrast levels are the same as those that do so for suprathreshold stimuli." The contribution of reduced CS and retinal illuminance to the age-related deficit on the temporal resolution of suprathreshold spatial stimuli was evaluated, revealing an apparent age-related reduction in retinal luminance as the major determinant of this spatiotemporal deficit, even at suprathreshold contrast levels. Culham and Kline (2002) concluded that their results indicated a loss in the temporal resolving properties of the senescent visual system for suprathreshold targets of low and intermediate spatial frequency. This deficit was not a function of low target contrast nor did it appear to be related to observer CS. Although age-related optical factors that limit retinal luminance appear to explain most of this deficit, neural factors may also be involved. The relative importance of each, as a function of task type, will need to be addressed in future research.

Numerous investigators have surmised that currently undetermined neural factors may play an important involvement in the results of combined low-contrast, dim luminance conditions. Berman, Navvab, Martin, Sheedy, and Tithof (2006) examined the near VA (400 mm distance) of 27 children aged 10 to 11 years old, through measurement by a licensed optometrist under two common fluorescent lamps of CCT 3600°K and 5500°K. Acuities were measured for three lighting conditions, either both lamps providing equal task luminance or a condition where the task and room luminance from the 5500°K lamps was set 50% lower. For the equal luminance condition, the results showed VA was significantly better ($p < 0.001$) under the higher CCT lamp with 24 of 27 children having better acuity. Paired t-tests comparing the lower luminance condition showed significantly less acuity resolution for the 5500°K lamps at the lower luminance, but no significant difference between the 3600°K lamps at the higher luminance, as compared with the 5500°K lamps at the lower luminance.

Early research by Oliver et al. (1997) assessed the alteration of anterior corneal topography by photorefractive keratectomy, which induced major changes to the optical aberrations of the eye. Six diopters (D) of myopia correction was attempted on one eye, in each of 50 patients, randomly allocating the treatment to one of three different regimens. Corneal spherical aberrations and coma-like aberrations both increased significantly following photorefractive keratectomy ($p < 0.001$), as did the mean spherical aberration coefficient. The corneal modulation transfer functions were reduced significantly following the photorefractive procedure. Corneal modulation transfer function calculations suggested that a significant loss of visual performance should be anticipated following photorefractive keratectomy, the effect being greatest for those with large pupil diameters. However, considerable procedural improvements have been implemented within PRK treatment paradigms, which theoretically have minimized such distortion-inducing effects. In the case of Army Aviators, if a potential patient is excluded from any of those treatment paradigms, then contact lens wear is now available as an alternative to most aviators, except for presbyopic pilots (i.e., those individuals with a decreased accommodative ability who are troubled by near reading targets at 16 in or less). Allard, Renaud, Molinatti, & Faubert (2013) and Arranz et al. (2012) evaluated the relative significance of optical and neural mechanisms in letter CS 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 (varying from 10 cd/m^2 to 600 cd/m^2) and surround luminances (varying from 1 cd/m^2 to 600 cd/m^2). The results revealed a significant influence of optical factors (e.g., pupil size variations and glare effects) on CS when the surround luminance changes; as well as a dominance of neural effects when the test contrast luminance changes.

Connolly and Barbour (2009) evaluated contrast thresholds relative to normoxia and hypoxia. The latter caused the contrast thresholds to increase at all light levels, but particularly under mesopic luminance. Hyperoxia decreased contrast thresholds, but only at the lowest light level. In general, hypoxia caused a reduction in mean pupil size while hyperoxia caused the pupil to dilate. Mild hypoxia degrades low CA progressively with decreasing mesopic luminance. Visual acuity is poor under the combined conditions of low luminance and low contrast; until recently, the effects of an altered oxygenation state on low-contrast visual performance in dim lighting were not well documented. Specifically, Connolly and Barbour (2009) examined the normobaric CA thresholds (CAT) of 12 healthy volunteers at three different luminance conditions (i.e., low photopic [12 cd/m^2]; upper mesopic [1 cd/m^2]; and mid-mesopic [0.1 cd/m^2]), while under three different oxygenation conditions (14.1% O_2; 100% O_2; and 21% O_2). Relative to normoxia, hypoxia caused the contrast thresholds to increase at all light levels, but particularly at mesopic luminance. Hyperoxia decreased contrast thresholds, but only at the lowest light level that had been measured (0.1 cd/m^2). In general, hypoxia caused a reduction in mean pupil size while hyperoxia caused the pupil to dilate. Mild hypoxia degraded low-contrast acuity progressively with decreasing mesopic luminance. At 0.1 cd/m^2, supplemental oxygen enhanced low-contrast acuity, implying that visual performance is oxygen-dependent in the mid-mesopic range, qualified by its being relative to baseline performance under mild hypoxia (at 3048 m or 10,000 feet). Therefore, supplemental oxygen can return functionally useful vision to lower light level thresholds previously affected by hypoxia. These findings potentially are relevant to contemporary military night flying, viewing the external scene directly, or through night vision devices, or when viewing dimly illuminated flight deck instrumentation.

Raymond, Lindblad, & Leibowitz (1984) noted that during a 1-min observation, the percentage of time a high spatial frequency grating can be detected is influenced by the contrast and spatial frequency of a second, superimposed and orthogonally oriented sine wave grating. Increasing the contrast of the second pattern aided detection of the first by providing a more effective accommodative stimulus. Interestingly, the function relating spatial frequency and the minimum contrast needed to activate accommodation is similar in shape to the classical CS function. However, an order of magnitude of increased contrast is required to stabilize accommodation than is required to simply detect a pattern. These results suggest that performance on visual tasks requiring sustained examination, rather than a brief detection flash, may be markedly impaired under low-contrast conditions. This effort sought to perform two independent methods of analyzing de-identified published visual performance (i.e., CA) data, using a classically structured meta-analysis of only the published studies that the two primary investigators have reached agreement on their meeting the formally identified eligibility standards (see Methods section) for the determination of visual performance CA. Range analyses representing a combination of globally accumulated data on each of the three CA conditions (i.e., decreased target contrast; decreased illuminance; as well as the combined condition of coincidently decreased contrast accompanied by low luminance was considered as key to a thorough understanding of the full potential for individual variability. It is widely understood that scotopic vision can be adversely affected by a lack of essential nutrients such as Vitamin A and zinc deficiency. In healthy individuals, studies have preliminarily addressed the effects of age, pupil size, and astigmatism on differences in scotopic visual abilities.

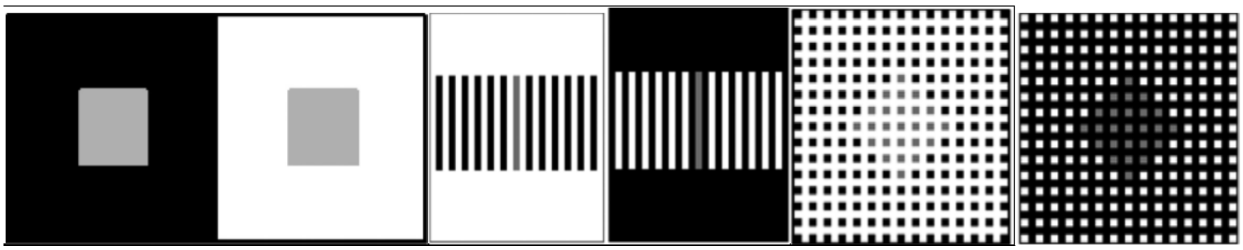

Figure 15. The three configurations shown here, known as reversed contrast, are based on unique contrast-comparison functional mechanisms, also termed the classical lightness contrast effect.

However, no effort has yet been made to describe the individual differences in dark adaptation, or to describe the individual differences in scotopic visual function of healthy observers, or to characterize the factors that influence these differences. These figures demonstrate three different configurations in which a gray target, totally surrounded by black can appear darker than an identical gray target, surrounded by white. Summarizing; the effect on the grays is the result of the combination of at least specific three factors, which are stronger when the displays are viewed from a distance.

1) color of the strips to which they belong (black strips induce lightening contrast);
2) color of the overall background (white background induces darkening contrast);
3) color of the flanking regions (white or black flanking regions induce lightening assimilation / or darkening assimilation).

Differences between normal observers may result from rod density, differential convergence of rod signals, extent of activation of distinct pathways, functional differences in proteins such as rhodopsin, or other, more general post-receptoral mechanisms. 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 acuity. However, few have looked at the combined challenge of altered contrast, while subject to decreased retinal luminance, a conditionally devised term, referred to as “contrast acuity.” A review of available studies on visual performance capability under either, or both of these two conditional variables (i.e., decreased target contrast in conjunction with conditions of decreased luminance, as well as each individual condition) was overdue. Wood and Owens (2005) investigated whether VA or CS, measured under a range of luminance conditions, could predict drivers’ recognition performance under real-world day and night road conditions. Changes in drivers’ recognition performance were more strongly predicted by CS than VA, when measured under standard photopic conditions. Interestingly, CS was highly correlated with VA measured under low-luminance conditions. Further analyses showed that recognition performance while driving is better predicted by combinations of two tests, either:

1) the photopic VA and the photopic CS tests are best analyzed to determine recognition performance capability, or
2) both the photopic and mesopic VA tests are analyzed for best recognition performance capability.

Wood and Owens (2005) confirmed that visibility is seriously degraded during night driving, and that the problem is greater for older drivers. These changes in real-world recognition performance were better predicted by a standard test of CS than by VA. Still better predictions can be obtained by the use of two vision tests. Current knowledge is unable to establish validity among the following conditional challenges: either both visual performance conditions must operate together in a conjunctive association, or each condition is individually and independently considered. Regarding visual CA, any of the above conditional performance influences can occur at varying performance levels, dependent on the specific operant conditions.

The overall limits of human sensory visual performance tolerance under realistically adverse operational conditions are yet to be fully defined (i.e., involving conditions of degraded contrast, accompanied by decreased luminance), although Bartholomew et al. (2016) established a good beginning to this process. The next four figures are illustrations of their process-comparisons of the VA and CS functions, including their illustrative interactions, found in Bartholomew et al. (2016). This visual system tolerance to debilitating conditions of decreased contrast and low luminance has been found to be highly variable across all tested individuals, such that a normal distribution is achieved. The controlling factors for this performance variability are poorly understood, with no current appreciation for how to even slightly improve one's combined CA performance. Conditions pertinent to visual function have a specific "go/no-go" organization, meaning awareness of a second visual stimulus is dependent upon it being of a specific size, intensity, color, or perceived hue for the second stimulus to be "discernable" (or perceived) to the observer. Snellen VA, described as a supra-threshold stimulus, accounts for detection, recognition and identification only of those items at or above a specific level of stimulation. Such a VA test ignores stimulus conditions that are slightly or considerably below the established threshold. Despite the noted shortfall in test parameters, the supra-threshold test easily permits both population normalization projections, as well as development of standardized performance endpoints (troubled little by performance variance or intolerance). Specific functional combinations are more readily discernable than others. Visual resolution can be differentially affected under differing luminance conditions, with performance in lower luminance conditions frequently being more sensitive to ocular dysfunction. In general, based on the agreement of several investigators conclusions (each based on their own results) is that strong visual performance in mesopic or scotopic conditions tend to predict strong photopic vision, but the reverse has clearly been shown to *not* necessarily hold true. Indeed, no single practical finding can be usefully reached for the prediction of mesopic performance under all viewing conditions, because it may *not* be achievable. Stockman and Sharpe (2006) concluded their series of studies with the statement that "mesopic vision, and mesopic luminous efficiency are complex. Any measure of mesopic performance is likely to be dependent upon several varied conditions (i.e., adaptation, spectral composition, spatial frequency, temporal frequency, retinal location, and retinal area)." Their concluding statement was "Clearly, this is not an area for the fainthearted."

Chromatic Issues

A key aspect regarding optical noise vs neural noise will lead to an assessment of blue or S-cone sensitivities. In evaluating the human cone mosaic, it is clear that the S-cones are differently distributed than the M- and L-cones (Curcio, Owsley, & Jackson, 1991). Blue light, as well as blue-sensitive cones (also termed S-cones), have attracted considerable interest within the psychophysical community regarding visual performance variability. On the physical optics side of the issue, blue light possesses a shorter wavelength than the other colors, meaning it is most subjected to increased scatter creating an adverse signal-to-noise ratio regarding neurological signaling. Furthermore, S-cones are the least numerous in the primate retina, comprising between 5 and 10% of all cones. They are widely scattered across the retina's mid-periphery on an even spacing scale (except for the S-cone free region in the central fovea, which is surrounded by a ring of evenly distributed S-, Medium wavelength- / green-sensitive cones (M-cones), and Long wavelength- / red-sensitive (L-cones) density (Ahnelt & Kolb, 2000 ; Hunt & Peichl, 2013)). The relative sparsity of the S-cone mosaic provides a perfect opportunity to probe the relationship between the sampling arrangement of the blue photoreceptors with reference to their perceptual performance. Williams et al. (1981) were able to map discrete peaks in psychophysical sensitivity that were spaced roughly 10 min of arc apart; it was thought these peaks corresponded to individual S-cones. In addition, the spectral sensitivity of the S-cone was quite different from that of the L- and M-cones, so that the isolation of S-cone mediated vision via selective adaptation to suppress the sensitivity of the L- and M-cones was relatively easy to accomplish (Wyszecki & Stiles, 1982). In the instance of the specific area of investigation regarding human CA variability, one aspect of the data search will concentrate on the selective suppression of S-cones, which is optimally related to the specialized visual performance issues under DVE.

CNS Neural Pathway Linkages

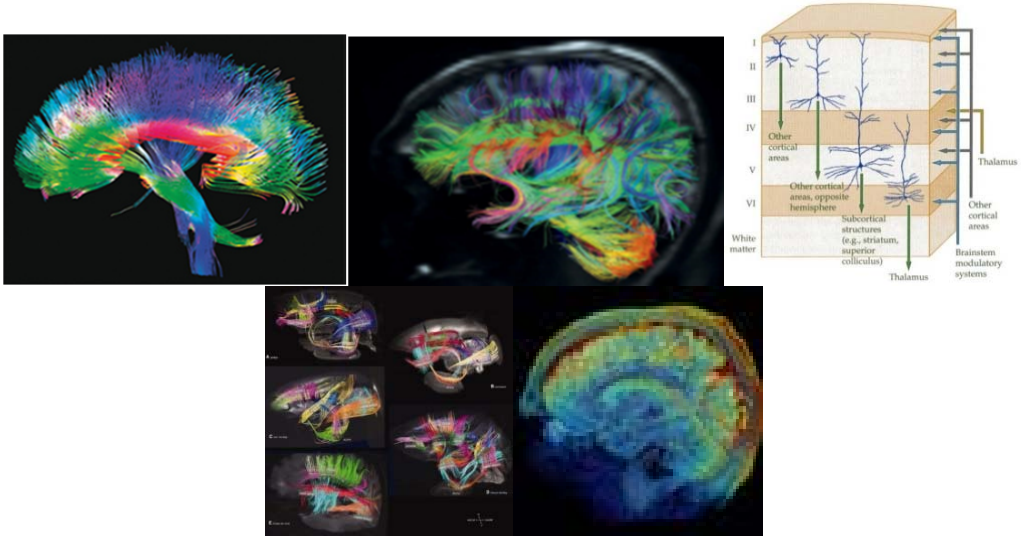

Figure 16. The originating neural centers and subsequent connections. The left-most photograph and the right-most drawing clearly indicate intra-cortical communicational processing occurs within a columnar organization. This organization of inter-cellular communication mimics the cornea's system, as well.

Decreases in visual resolution occurring at low-contrast and decreased light levels appear to be subordinate or secondary to internal Central Nervous System (CNS)-based neural factors, and not from optical blur or spherical aberration secondary to increased pupil size. Yet, several investigators have recognized that microfluctuations within the accommodative system, occurring once again under a setting of low-contrast and decreased illuminance, will additionally contribute to decreased visual resolution. Similarly, eye movement variability, which also increases in the dark, directly contributes to increased fixational instability and decreased visual resolution. The payoff in providing a medical evidence-based array of understanding of threshold-level visual function influences would allow the development of a physical performance standard, linked to operational performance conditions and abilities, against which selection of ideal candidates for specialized duty could be based. The structure of the brain as a product of morphogenesis is difficult to reconcile with the observed complexity of cerebral connectivity. Weeden et al. (2012) therefore analyzed relationships of adjacency and crossing between cerebral fiber pathways in four nonhuman primate species and in humans by using diffusion magnetic resonance imaging. The cerebral fiber pathways formed a rectilinear three-dimensional grid continuous with the three principal axes of development. Cortical pathways formed parallel sheets of interwoven paths in the longitudinal and medio-lateral axes, in which major pathways were local condensations. Cross-species homology was strong and showed emergence of complex gyral connectivity by continuous elaboration of this grid structure. This architecture naturally supports functional spatio-temporal coherence, developmental path-finding, and incremental rewiring with correlated adaptation of structure and function in cerebral plasticity and evolution.

The organizing principles of cerebral connectivity remain unclear. In the brainstem and spinal cord, fiber pathways are organized as parallel families derived from the three principal axes of embryonic development: the rostro-caudal, the medio-lateral (or proximo-distal), and the dorso-ventral. In the forebrain of advanced species, however, corresponding patterns of connectivity have yet to be established. Many studies of evolution, development, and gene expression point to a geometric organization of cerebral fiber pathways similar to that of the brainstem, and functional studies also suggest that connectivity is geometrically organized. Several leading theories of cerebral function propose geometric organization at multiple scales. However, high-resolution studies of cerebral connectivity with tract tracers have given only limited evidence of geometric organization. A challenge in the investigation of cerebral structure and connectivity can be traced to the common occurrence of distinct pathways within the same small volumes of tissue, or "path crossing." Crossing is a pervasive feature of brain structure and may be essential for efficient connectivity. Owing to crossing, the mapping of connectivity must untangle pathways from cellular to macroscopic scales, simultaneously. This can be accomplished with tract tracer methods, which are now considered a gold standard. Tracer studies inject compounds into the live brain and allow them to disperse by means of axonal transport, marking individual axons over large distances. However, these can map only a small fraction of the pathways in any single brain and are not feasible in humans. The discovery and analysis of the structural relationships between pathways, and their context within overall cerebral connectivity, will remain challenging.

To address these limitations, methods have been developed to map the fiber pathways of the brain through use of diffusion magnetic resonance imaging (MRI). Diffusion MRI creates multidimensional contrast that is representative of the distribution of fiber orientations at each location in the tissue. Diffusion MRI is noninvasive, applicable to humans, and able to map the connecting anatomy of a single brain in its entirety. Diffusion spectrum MRI (DSI) can acquire whole-brain specimen maps; in the rhesus monkey, central and subcortical grid structures, including those of the major frontal sulci (principal, arcuate, central), fit together continuously like a jigsaw puzzle. It is hypothesized that the complex connectivity of the cerebral mantle represents a continuous elaboration of the simpler core. Investigators have demonstrated that the fiber pathways of the forebrain are organized as a highly curved three-dimensional grid derived from the principal axes of development. This structure has a natural interpretation; the pathways of the brain follow a base-plan established by the three chemotactic gradients of early embryogenesis. Thus, the pathways of the mature brain present an image of these three primordial gradients, which become deformed throughout the stages of development.

Overall, Bartholomew, et al. (2016) found that scotopic VA performance, and scotopic CS performance were both significantly correlated with the absolute detection threshold facility (or speed) of dark adaptation ($p < 0.001$). Visual acuity performance in photopic conditions was significantly correlated with VA performance under scotopic conditions ($p < 0.001$), yet the relationship explained only 4.1% of the overall variance. Photopic CS score performance was significantly correlated with scotopic CS score performance ($p < 0.001$) but explained only 2.5% of the overall variance. Test, re-test for both photopic VA and CS; and test, re-test scotopic VA and CS varied only by ±1 line under a logMAR system. Genetic analyses of 139 candidate genes historically annotated as being involved in photo-transduction pathways, and in retinol metabolic pathways; or reaching for more distant relationships, sought genetic-implicated Mendelian diseases linked to night vision defects; and still found no significantly associated variants. In examining young individuals with excellent photopic vision, Kefalov (2012) found a wide variation in performance that is largely unexplained by a range of factors such as Circadian preference, photopic visual performance, intelligence, or eye characteristics. Combined with high test-retest agreement and the existence of diseases uniquely targeting rod systems, their findings argue for a strong genetic component of healthy variation in night vision that essentially beckons further exploratory research, in search of the underlying governing aspects. Bartholomew et al. (2016) further measured contrast sensitivity, low contrast VA, and luminance thresholds in the central visual field (30°) for a group of 38 adult subjects, with and without a coated yellow lens filter (482-nm cutoff) under mesopic conditions. The CS mean, under normal contrast conditions was significantly better with the yellow filter at low- and middle-range spatial frequencies (1.5 cycles/degree p = 0.002) and 6 cycles/degree (p = 0.02). However, under conditions of only 5% contrast, the mesopic low-contrast VA improved significantly (p = 0.004) when interposing the (482-nm cutoff) yellow filter. Chauhan and Charman (1993), in evaluating night-time road luminances in the UK, have found them to be on the order of 1 cd/m^2. When driving on well-lit urban main roads, luminance values of pedestrians and other objects of interest (e.g., traffic signs) are even lower, into the range of 0.01–0.25 cd/m^2. Absolute threshold values at these mesopic levels, where both rods and cones mediate perception, ranged between 5 x 10^4 and 5 x 10^3 cd/m^2. Charman concluded with the statement that it is now well established that many aspects of visual performance, such as spatial resolution, stereopsis, accommodation, and reaction time deteriorate under conditions of low illumination (Arumi, Chauhan, Charman, 1997).

The above data indicate that the letter CS determined under both photopic and mesopic conditions diminished significantly with age. The dividing line for the lower limit of both normal photopic and mesopic CS values has been proposed to be at age 50 (Elliott, Whitaker, Bonette, 1990). Sloane, Owsley, and Alvarez (1988) found that older adults tended to experience significant losses in spatial CS under low environmental light levels. The evolving methods of visual resolution assessment are seeking to monitor visual performance at, or very near the basic threshold levels of function (i.e., under very dim conditions of low illumination, accompanied by minimal contrasting target conditions). Therefore, within the two separate means of examining historical visual performance assessments, two differing methods of VA determination were often used as a check against gross, supra-threshold visual performance, as well as subtle changes in visual performance, using target conditions that are increasingly compromised (as in DVE) by both decreased illuminance, decreasing contrast, or a combination of both. The latter condition can either be assessed using a CS apparatus (which is cumbersome and requires considerable time), or by combined charts which can probe both acuity and contrast simultaneously (which are faster to perform, but are self-limiting in their spatial-frequency determining utility). Internal comparisons of VA by Snellen chart, or standard clinical acuities under low-contrast/low-illuminance methods were not influenced by type of contact lens worn, by the wear of spectacles, by age, or by entrance and exit assessment. External comparisons of the two acuity measurement methods emphasized statistically significant differences that have potential for future use in identifying superior visual performers. If this potential is realized, then standards for visual assessment in military aviation, and the military in general, will most certainly need to be modernized.

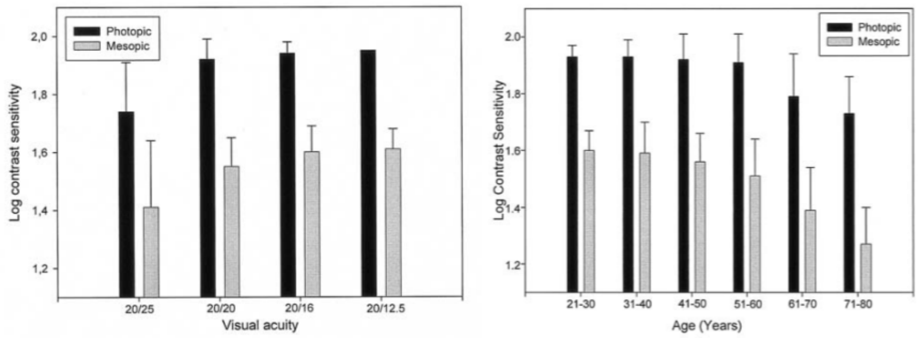

Figure 17. (a) Photopic and mesopic mean log CS according to photopic VA. Vertical lines indicate the standard deviation. *(b)* Mean log CS across age groups tested under photopic and mesopic luminance conditions. Vertical lines indicate the standard deviation. Puell et al. Contrast Sensitivity Under Mesopic Luminance Conditions. J Refract Surg. 2004; 20:484-488.

In Puell et al. (2004), the peak mesopic CA occurred at approximately logMAR 1.56 (left-hand chart, Figure 17). Again, the age range of Puell et al.'s subjects is much, much greater, using subjects from age 21 to age 80. Their cross-sectional study was performed on 292 drivers stratified by age into six groups. That wider range of subjects would reasonably result in a wider range of responses, as well as higher response errors due to the age extremes. Reviewing the mean logMAR CA of the youngest subjects participating in the Puell et al. study with the mean logMAR CA in the original USAARL study, we find the mean values to almost the same. The partial Puell mean for the two youngest age groups was logMAR 0.30, which approximate the USAARL subject distribution. The USAARL mean of logMAR 0.40 is moderately close in comparison. Given the separate age group ranges, it is understandable for their mean data to approximate one another.

Discussion

The establishment of CS norms or standards regarding acceptable CS performance levels under mesopic conditions would assist in determining if an exhibited decrease in dark adaptation or CS is pathologic in nature. Alternatively, determination of the acceptable variance in human tolerance variability to the dim, poorly illuminated conditions would also serve as an excellent reference point. Finally, the utilization of high-contrast photopic VA 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. Yet, photopic high-contrast VA is *not* an appropriate visual performance reference when predicting one's visual performance under degraded visual conditions. Additionally, mesopic and/or low-contrast visual testing *do not* correlate at all with high-contrast visual performance testing, nor will high-contrast photopic visual performance testing correlate well with dark adaptation facility testing. 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. In support of wave-front aberration metrics, Pesudovs, Marsack, Donnelly, Thibos, and Applegate (2004) explored whether photopic high-contrast VA 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, mesopic high-contrast conditions, and mesopic 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 and between acuity, and wavefront aberration metrics. The two photopic measures were poorly distributed, but the two mesopic measures were normally distributed (a characteristic that many of the previously discussed studies also exhibited). While strong correlations existed between the VA variables regarding photopic testing, low-contrast and/or mesopic acuity testing provided significantly different references regarding wavefront metrics. Consequently, the conclusion was reached that physical optics effects (native, or inherent to the eye) provided improved correlation with VA under both mesopic-based low-luminance and low-contrast conditions, making wavefront aberration metrics their recommended visual performance test that is most predictive of visual capability under DVE visual performance conditions. 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. 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 is 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.

	y_1	y_2	y_3	y_4	y_5	y_6	y_7	y_8	y_9	y_{10}
x_1	36	4	1	1	0	0	0	0	0	0
x_2	10	17	21	3	0	0	0	0	0	0
x_3	2	12	13	17	4	0	0	0	0	0
x_4	1	5	6	9	11	2	0	0	0	0
x_5	0	0	1	16	22	20	0	0	0	0
x_6	0	0	0	2	8	25	13	0	0	0
x_7	0	0	0	3	5	11	27	5	0	0
x_8	0	0	0	0	0	5	14	30	4	0
x_9	0	0	0	0	0	0	2	15	29	4
x_{10}	0	0	0	0	0	0	0	0	11	33
y_k^{total}	49	38	42	51	50	63	56	50	44	37

Figure 18. Typical experimental results for the categorical matrix obtained from a single subject B. Total number of points is 480 and the number of categories is 20. The Farther from the edges, the tendency toward normal distribution is observed in each row. Furthermore, the distribution of responses, $p^{\sim}(y_k)$, approximates a uniform one, as indicated by the tabulated values of $y_{k,}^{total}$ listed at the bottom.

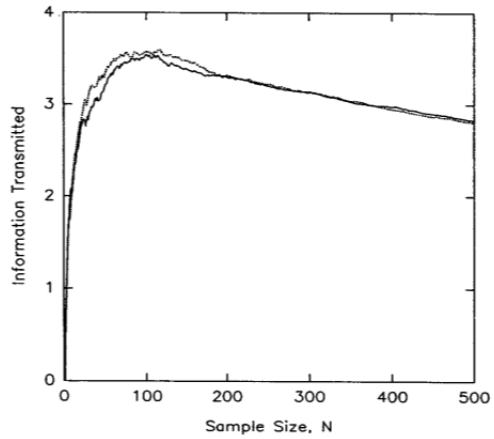

Figure 19. Results of a simulation are compared to measured values. The simulated curve (solid curve) was generated using the average row variance obtained from a subject's responses (subject J). The dashed curve indicates the information as evaluated from the measured data of the same subject.

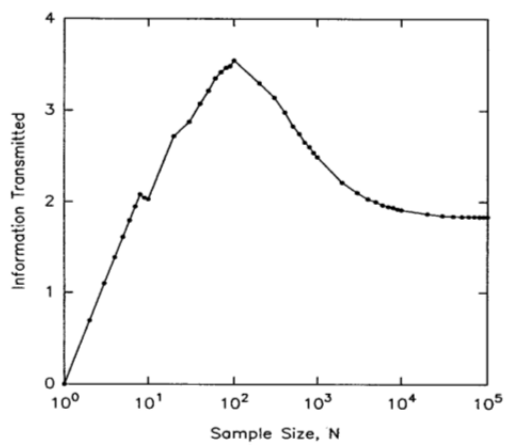

Figure 20. Simulated values (") of information transmitted for large values of N, as opposed to the limited number of repetitions shown in the preceding figure. The same variance was used in both the previous simulation, and the current simulation.

Baccus and Meister (2002) examined how the visual system adapts to the magnitude of contrast intensity fluctuations; this process 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, they 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 adapt to contrast. 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 CA performance (particularly while under DVE conditions). Since CA is an individualized visual performance characteristic resulting from several unique CNS-processing approaches by the visual system, we sought to stratify individual CA threshold sensitivity influences, as well as to determine their underlying central nervous system processing functions responsible for this overall individual variation. The accomplishment of detailed anatomical and visual psychophysical analyses on characterized samples of subject stratification categories ought to assist in pinpointing the underlying contributors to the exhibited thresholds of the top 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 visual performance end-result.

Previous studies related to gaining an understanding of the underlying governing factors are highly varied in their approach and results. Sole , Rigal, and Peyresblanques. (1984), found ‘cyaninoside chloride’ to significantly improve photopic VA ($p < 0.05$) 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 it toward a military performance category (e.g., sniper), in order to maximize performance. When feasible, the intention to seek to expand performance characteristics is always a stimulus. However, a medical research goal of performance enhancement is not necessarily within the expected research performance limits of our mission. The brain’s cortical processing centers cross-connect along numerous channels, allowing signal-gating, which enables further signal refinement. Decreases in visual resolution occur at lower light levels resulting from central neural-controlled factors associated with decreasing retinal illuminance, 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. Similarly, eye movement variability also increases in the dark, directly contributing to increased fixational instability and decreased visual resolution.

A number of complex theories regarding the underlying cause of mesopic CA 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. This overall effort is anticipated to be as a 3-year overall project, consisting of the currently read meta-analysis report after the first year (i.e., FY16). This meta-analysis, which will be closely followed by a 2-year human use study, in which investigators will seek to determine the underlying causes that appear to be governing individual CA variability. Determination of the underlying contributors toward that varied performance ability will be analyzed within the context of the anticipated visual performance ranges established by the meta-analysis. Color identification at low light levels is also important for the development of performance-based standards design-characterization, with regard to military applications. Several draft models have already been experimentally developed under unaided conditions, as well as under helmet-mounted display (HMD) conditions. However the relationship between background color as seen through a display unit, that is overlaid with an aircraft's color-based output display is too complex for this specific manuscript to consider at the moment, other than to acknowledge the problem of integrating different color outputs or conditions as they are interspersed within a computer display. 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. 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.

US Feet(20/20)		LogMAR(0)
20	10	-0.3
20	12.5	-0.2
20	16	-0.1
20	20	0
20	25	0.1
20	32	0.2
20	40	0.3
20	50	0.4
20	63	0.5
20	80	0.6
20	100	0.7
20	125	0.8
20	160	0.9
20	200	1.0
20	250	1.1
20	320	1.2
20	400	1.3
20	500	1.4
20	630	1.5
20	800	1.6
20	1000	1.7
20	1260	1.8
20	1600	1.9
20	2000	2.0

Figure 21. A visual acuity logMAR conversion chart, which is of use when following the discussion regarding the implantation of diffractive-refractive lenses.

As the desire for spectacle independence following cataract surgery has grown, so does interest in the implantation of multifocal intraocular lenses. However, glare phenomena, reduced intermediate vision, and loss of image quality are known problems associated with this new generation of intra-ocular lenses, based on very similar experiences with multifocal hydrophilic and silicone-hydrophilic polymer contact lenses. A comparison of the functional results (achieved by implantation of the diffractive-refractive lenses), to the results achieved from implanting monofocal lenses was presented by Anton, Böhringer, Bach, Reinhard, and Birnbaum (2014). A prospective data analysis followed ten patients who received bifocal intraocular lenses, and ten patients who received monofocal intraocular lenses. Lenses were always implanted in both eyes. In each group VA and CS was assessed with the Freiburg Vison Test at multiple distances ranging from 0.5 to 5.0 m. Additionally, near vision was assessed with the Birkhaeuser charts. An evaluation of the photopic phenomena was achieved, along with patient satisfaction using a standardized questionnaire. The mean monocular results for the control group's distance VA was logMAR -0.05 ± 0.14. The best-corrected monocular distance acuity was logMAR -0.03 ± 0.06 logMAR; the binocular acuity was slightly better at logMAR -0.15 ± 0.07. The mean monocular near VA was logMAR 0.92 ± 0.27, and the mean binocular near VA measured logMAR 0.74 ± 0.24.

Critical Aspects of Optimal Visual Performers

One of the major influences upon CA visual performance is the individual observer's age, which has drawn considerable attention. Head and eye tracker technology can reveal the critical functional characteristics regarding the effective use of both head- and eye-movement, in-tandem. The IR scene and symbology information is normally seen on the primary flight display of a helicopter, or on its flight simulator instrument panel emulation. Combined head and eye movement analyses serve to introduce an in-tandem function, which is an experiential factor associated with age because it is not seen in younger subjects. A wide variety of additional factors, all with the potential to influence visual resolution (corneal distortions, lenticular alignment, aspect relationship errors, fusional and stereoscopic errors, as well as numerous anatomical optical system variations) can cumulatively contribute to reduced image clarity, as well. However, neural processing applications could partially balance those confounding effects from anatomical variation. This neurological adaptational ability has previously been identified as a critical factor related to visual recovery from refractive surgery. The conceptual framework for providing a global assessment of threshold-linked visual performance is dependent, to varying degrees of influence, upon three primary factors:

- Optical factors (i.e., pupil size and shape; corneal shape, lenticular shape, and overall ocular shape changes over time) have been identified as a likely predominant influence responsible for affecting CA.
- Neural, adaptational factors as the predominant influence responsible for affecting CA (i.e., when image presentation is under low-contrast, and retinal illuminance is decremented).
- Accessory physical factors, other than optical (e.g., degree of macular pigmentation, or degree of photopigment density).

Lasagno et al. (2014) measured suprathreshold visual efficiency in different age groups, recognizing two Landolt ring orientations, in combination with answering some visual discomfort questions. Results show: the oldest group (ages 60 – 67) needed more than 3 times the time required by the youngest group (ages 25 – 30) to perform the task. However, in terms of visual discomfort, there are no noticeable effects regarding the disturbance or the sensation of reduction of mobility produced by the lighting changes in the transitional space among the three different age groups studied. Yet, shortly after the Lasagno study, Joulan, Hautière, and Brémond (2011) developed an analytical age-dependent model of CS functions in an ageing sample. The Contrast Sensitivity Function (CSF) described how the visibility of a grating depended on the stimulus spatial frequency. Age-dependent analytical models of the cone densities, combined with the ganglion cell densities directly reflected 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. The conceptual framework for providing a global assessment of visual performance can be reduced to these two primary visual performance characteristic factors:

a) either optical factors (i.e., pupil size or corneal shape variation) are responsible for affecting CA; or
b) neural adaptational effects are responsible for affecting CA (e.g., when test chart illuminance changes).

Since comparative pupil sizes can vary (normal manifest variations due to luminance conditions vs cycloplegic, or dilated, non-accommodative pupil), then issue "a)" is pertinent in this specific case. In the singular assessment considered here, comprehensive higher-order aberrations are evident in both manifest and cycloplegic subject conditions to an equal extent, since each subject serves as his or her own control. By controlling test chart luminance (as well as any other pertinent variable sources) and varying only pupil size, one is able to isolate the optical effects of simple spherical aberration. Defocus, which is optical blur in the absence of a dilated pupil, is not operant because refractions under both conditions can be performed to "best visual acuity" or BVA. A wide variety of potentially adverse influences on visual resolution (corneal surface distortions, lenticular alignment errors, 3-dimensional to 2-dimensional (3D - 2D) aspect relationships, fusional and depth perception errors, as well as optical system variations) will all yield reduced image clarity/resolving power. However, system-based neural processing-correction applications could factor out some of those influences. Considering that these two processes are isolated to two completely different centers of visual performance, facility of dark adaptation is entirely centered within the retina; while the visual resolution processes regarding detailed resolution processing occurs in the occipital cortex. Despite their differing processing centers, both systems operate on a remarkable characteristically parallel process, suggesting an as-yet-to-be undiscovered, undocumented over-riding control center above that of both dark adaptation and visual resolution.

In fact, this neurological adaptational ability has been identified as a factor related to recovery from refractive surgery. Consequently, fund investment in this human dimension "technology" to identify those individuals with superior CA resolution could very well prove to be the least costly or most cost-effective solution to safe, effective combat flight under brown-out conditions. Holladay, Dudeja, and Chang (1999) presented a defense of their Snellen acuity conversion formulas into the logMAR format, modeling the mathematical progression of this transition from a discrete, nonparametric unit of visual performance measurement, to a continuous parametric variable to a visual performance measurement. Visual perception is a cognitive representation of the three-dimensional world as a function of a curved, concave photo-sensor array (i.e., rods and cones on the retina). Modern technology increasingly presents information via flat panel arrays; such displays present a progressive sequence of distortions and aberrations demanding visual perceptual adaptation. Furthermore, visual resolution or acuity has traditionally been measured via a discrete variable process, as opposed to more recent research seeking to document a combined continuous performance index involving both visual resolution and CS, termed CA, a combined nomenclature concept introduced earlier in this paper. The goal of this effort, then, is to utilize this logarithmic analytical performance index, commonly referred to as logMAR acuity in our collaborative investigation into the CA variation condition.

Allard, Renaud, Molinatti, and Faubert (2013) and Arranz et al. (2012) evaluated the relative significance of optical and neural mechanisms in letter CS 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 10 cd/m^2 to 600 cd/m^2) and surround luminances (from 1 cd/m^2 to 600 cd/m^2). The results revealed a significant influence of optical factors (e.g., pupil size variations, and glare effects) on CS when the surround luminance changes; as well as a dominance of neural effects when the test contrast luminance changes. Rabin and Wicks (1996) presented recent evidence suggesting that the small letter CS is more sensitive than traditional Snellen VA testing 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 VA to spherical and astigmatic blur, low luminance, and vision with two eyes vs. one eye. 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.

Hiraoka et al. (2015) concluded, after reviewing a range of classical studies, that factors other than refraction influence CA under low-luminance conditions. The brain's visual cortical processing centers cross-connect along numerous channels, allowing the application of signal control or -gating, which enables 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 increased pupil size, or an induced myopic shift. Microfluctuations in accommodation within a decreased luminance setting also directly contribute to decreased visual resolution. Similarly, eye movement variability (e.g. saccades and smooth pursuit) exhibit increases in the dark, directly contributing to increased fixational instability and decreased visual resolution. A number of theories regarding the underlying cause of mesopic CA 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 (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.

Conclusions

1) Photopic VA testing alone cannot consistently predict one's visual abilities under conditions of DVE (i.e., mesopic conditions, under decremented contrast).

2) Photopic, scotopic, and mesopic CAs are subject to differing post-receptoral pathways through which the cone and rod signals are transmitted. Objective wavefront aberration metrics

better correlate with low-contrast mesopic resolution, suggesting this expensive system as the mesopic visual performance test of choice.

3) However, combined VA and CS tests are the most cost effective and possible most efficient means of identifying those with superior visual performance abilities. No one test can measure both visual performance characteristics. Yet, the Rabin SLCT and the Pelli-Robson test systems each probe one vastly different aspect of the CS function, necessitating the use of both testing systems to identify optimal visual performers.

4) Despite that, the high between-subjects variance concerning scotopic and mesopic visual performance is a critical gap in our scientific understanding of the underlying mechanisms of individual visual performance capability.

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