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Visual information provided to the modern military aircrew member accounts for the preponderance of data contributing to situational awareness. Although long recognized as a critical factor in aviation, as a result of advancing tecnological developments, color vision is emerging as an ever-increasing critical requirement in modern and future cockpits. Despite that premise, the modern battlefield is characterized by a vast array of technological weaponry that increases the threat to the visual system and dictates effective countermeasures that compromise visual performance in general and color perception in specific. This paper will review the aeromedical basis of color testing developments and issues that effect aeromedical decisions in color standards and performance as they relate to the modern military aircrew member. It will include an update on color vision issues raised by protective equipment such as selective waveband filters that include sunglass materials and laser protective eyewear/visors. Color-related aircraft accident issues will be addressed.

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COLOR VISION ISSUES IN MODERN MILITARY AVIATION
Alternate Title: "THE SEARCH FOR THE ABOMINABLE CONEMAN"

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SUMMARY

Visual information provided to the modern military aircrew member accounts for the preponderance of data contributing to situational awareness. Although long recognized as a critical factor in aviation, as a result of advancing technological developments, color vision is emerging as an ever-increasing critical requirement in modern and future cockpits. Despite that premise, the modern battlefield is characterized by a vast array of technological weaponry that increases the threat to the visual system and dictates effective countermeasures that compromise visual performance in general and color perception in specific. This paper will review the aeromedical basis of color testing developments and issues that effect aeromedical decisions in color standards and performance as they relate to the modern military aircrew member. It will include an update on color vision issues raised by protective equipment such as selective waveband filters that include sunglass materials and laser protective eyewear/visors. Color-related aircraft accident issues will be addressed.

LIST OF ACRONYMS

LEP	laser eye protection
SAM	School of Aerospace Medicine
AO	American Optical
PIP	Pseudoisochromatic plates
FM	Farnsworth-Munsell
CTT	color threshold tester
FALANT	Farnsworth Lantern
R/G	red/green
B/Y	blue/yellow
VASI	Visual Approach Slope Indicator
FLIT	fighter lead-in training
USAF	United Stated Air Force
UPT	undergraduate pilot training

I. INTRODUCTION

The modern combat arena is a multifaceted sophisticated techno-extravaganza. Scientific development of complex weapon systems has advanced almost exponentially. These lethal gizmos produce a kaleidoscopic universe of electronic symbology and information, primarily focused at the human element cradled within the system. Laser technology exploits susceptibilities of that human system. Defensive mechanisms, selected to protect and optimize the human interface use selective waveband filters, themselves inducing additional visual handicaps. The modern cockpit has evolved into a montage of colored symbology and cues presented in a visual blitzkrieg under task-saturated and hostile conditions. At no other time in the history of aviation has any facet of the visual system been more challenged than color discrimination is today. Engineers design multicolored displays hoping to facilitate information transfer between the aircraft and its master, but often paradoxically exceed physiological realities. The stakes are, indeed, high; survivability and mission completeness essential, political sensitivities, keen.

This paper addresses relevant color issues in the modern cockpit environment of today and tomorrow. Can we continue to expect pilots harvested from the normal population to visually cope, survive, and optimally couple with weapon systems that rely so heavily on color-based cues and which are then paradoxically degraded further by virtue of required protective equipment? One question emerges that impacts on aeromedical decision-making today and in the future: Does "Superconeman" exist, do we need him, and should we, as aeromedical consultants, embark on a journey in search of an "Abominable Coneman"?

It is appropriate to review the historical role of color vision in aviation and the selection standards that for 75 years have governed our approach to aviation color vision issues.

II. HISTORY OF COLOR VISION STANDARDS IN THE U.S. AIR FORCE

We begin by recalling a profound historical statement: "The proper recognition of color plays an important part in the success of all flyers. On the maps generally used by observers, the woods are green, rivers are blue, roads are yellow, railroads are black, and towns are brown. Skyrockets with a parachute are white, red and green, and cartridges--with and without parachutes--are of similar colors. Bengal flares, which are used in woods and heavy underbrush, are red and white. Aerodromes use red and green or white lights for homecoming planes, while the planes carry a red light on the port side and green light on the starboard side." This description is part of a paragraph taken from <u>Aviation Medicine in the A. E. F.</u>, from the chapter "The Eye in Aviation", written in 1919 by Col W. H. Wilmer and Maj Conrad Behrens (1). It contains much that is still important in flying aircraft today. During WW I, medical examiners felt that color vision testing was an important part of the physical examination of applicants for the aviation section of the Signal Corps. Testing for color deficiencies was done by the Jennings Self-Recording Color Test. Instructions were given that stated that if a Jennings test was not available, the medical officer should select a skein of any shade of red or green worsted and have the candidate select in separate piles all skeins containing red or green. If confusion was still present, colored lights at 20 feet should be used as a test before rejecting a candidate (2). It is evident that, even at the very onset, there were color vision testing problems. Between WW I and the onset of WW II, the SAM Department of Ophthalmology at Randolph Field, Texas, carried out a series of tests to detect color blindness. Experimentation was carried on with Holmgren skeins, the Jennings Self-Recording Test, Stillings PIP and Williams Lantern Test. It was recommended in 1935 that the Ishihara Test be adopted for color vision testing of aviation candidates (3). When the Ishihara test was first included in the examination, those who failed were rejected, but by 1940, several other tests, such as the Stillings PIP, Holmgren yarn matching and lantern tests, were also used to examine the extent of color blindness (4). The authorized tests for central color vision in 1941 were the Ishihara or Stillings PIP and Holmgren skein of yarn.

During WW II, a large number of studies on color vision were performed at the Army Air Corps SAM at Randolph Field. Most of these were accomplished under the direction of Louise L. Sloan, Ph.D. At the time these studies were initiated in 1942, four tests of color vision were authorized for use by the U.S. Army Air Corps. There were two basic tests--the Ishihara PIP (8th ed.) and the AO PIP--and two adjunct tests--the Holmgren wool test and SAM lantern test. Ability to pass the adjunct tests was used to qualify candidates as "color safe" under certain conditions. Regulations were rather vague; consequently, it was left to the individual examiner to select a testing device and method of scoring to distinguish between those who did and did not meet this criterion. Between 1942 and 1945, numerous tests were investigated at Randolph Field, such as the AO PIP, Rabkin polychromatic plates, SAM anomaloscope, Rand anomaloscope (Bausch and Lomb), Intrasociety Color Console (ISCC), Single Judgment Test, Eastman Hue Discrimination Test, FM 100-Hue Test, Terrain Test, and Peckman Vision Test. Also, a major effort was put forth in testing a number of lanterns; the Canadian Lantern and SAM CTT were the major efforts. The sum of these investigations was that, in 1943, the AO Abridged Set of PIP was selected as the most suitable basic test. This abridged version was composed of 17 tests and 2 demonstration plates. Of the quantitative tests investigated, the SAM CTT was rated the most satisfactory to classify flying personnel (5). These tests continued when the USAF became a separate service in 1947 and culminated in the assembling of the AO 15-Plate Test (14 test plates and 1 demonstration plate) in 1951. This set was adopted in 1953 as the USAF official color vision screening test. It's still used today except that in 1985, the AO plates were purchased by the Richmond Company and are now known as Richmond plates. Dvorine color plates could also be used in place of the AO plates. The Dvorine plates were printed in two volumes in 1944. The second edition, published in 1953 under the title "Dvorine Pseudoisochromatic Plates", also had 14 diagnostic plates and 1 demonstration plate. These plates are still used; however, they are no longer being manufactured (6). Today the only testing charts are the Richmond PIP.

From 1959 through 1984, the AO and Dvorine 15-Plate Tests were used interchangeably and were the first tests administered for aviation candidates. The causes for rejection were 5 or more incorrect responses on either set of plates. However, a test failure using the plates required testing by the SAM CTT. The CTT had 64 presentations; a score of 50 or better was passing (7). The USAF followed the example of the U.S. Navy, allowing mildly color-defectives to enter flying training. The U.S. Navy had used the FALANT to accomplish the same thing.

In 1988, the SAM CTT was removed from the inventory and the FALANT was substituted for the CTT. An aviation candidate who fails the Richmond PIP may still qualify if he passes the FALANT. Table 1 shows a chronological listing of the color vision qualifying tests used by the U.S. Army Air Corps and the USAF (8).

DATE	TESTS
1918	Jennings Self-Recording Color Test
1935	Ishihara PIP
1941	Ishihara or Stillings PIP
1942	Ishihara-AO PIP
1943	AO PIP test (17 test plates, 2 demonstration plates) SAM CTT (quantitative test developed)
1953	AO Isochromatic Plate Test (14 test plates, 1 demonstration plate)
1959	Dvorine PIP (14 test plates, 1 demonstration plate)
1959-84	AO and Dvorine for *FC I and IA - SAM CTT if plates failed
1985	Richmond plates replaced AO PIP for FC I and IA
1988	SAM CTT replaced by FALANT; passing the FALANT after PIP failure qualifies for FC I, IA and II

*FC I and IA = pilot (I) and navigator (IA) applicants

Thus, this testing methodology is designed to allow all trichromats and mild anomalous trichromats (R/G) to fly. More severe anomalous trichromats (R/G) and dichromats are not allowed to fly. B/Y assessment is not performed. Can we continue to support existing standards, or has the time come for us to employ a more rigid approach to reduce the impact of color vision deficits in future aviators? A review of modern-era military and civilian aircraft operations reveals that there have been, and continues to be, color-related factors that aggravate, compromise, and complicate flight operations. In some cases, aircraft have been lost. Surprisingly, these incidents have been few. It is highly probable that current color-screening methods have been as effective as anticipated, or perhaps color vision is not as critical as thought. Can these same screening methodologies continue to ensure the safety of our aircrews and mission completion in a color-complicated future? Also, there remain considerable unknowns with respect to causative factors of aircraft accidents and, in the case of retrospective database searches, often there is no stipulation that specifically requires color-vision-related data storage (USAF). We would like to present examples where color deficiencies are known to have played a significant role, either in task complication, a near mishap, or an aircraft accident, each provoking a different thought regarding current policy.

Examples

1. A 24-year-old A-10 pilot with 350 total flying hours was grounded without waiver after evaluation revealed the following data. He failed the FALANT but passed the CTT on initial entry physical exam at the Air Force Academy (AFA). On two reevaluations at the examinee's request, he failed the CTT. He failed the PIP (4/14 correct) and FALANT on 2 of 3 trials during his commissioning physical exam prior to graduating from the AFA. However, records indicated that he was qualified for and entered UPT. The pilot reported that during UPT he could never use the VASI lights on landing approach because he could not discriminate between the different color presentations (red/red = glideslope too low; white/white = glideslope too high; red/white = correct glideslope. Otherwise, neither he nor his instructors reported any difficulties during UPT.

He went on to FLIT and flew the T-38. On one flight, a group of tan-colored coyotes crossing the runway were unobserved by the pilot and his instructor pilot took the aircraft controls to avoid striking the animals. The pilot completed FLIT with no other difficulties. He then began training in the A-10. From the beginning of training, he noted difficulty identifying other green-colored A-10s flying at low level over green terrain. He also reported having difficulty with crossover turns, night refueling, rejoins in close formation, low-level formation flying, and night flying, and continued difficulty with the VASI light system. He reported that he was uncertain whether his perceived difficulties were a result of his color deficit or were normal problems experienced by most pilots. After reporting to his first A-10 squadron, his concerns led him to the flight surgeon, stating that he felt he was endangering himself and others while flying. He failed both the PIP and FALANT color tests. Extensive evaluation found severe protanopia, presumably congenital; however, a progressive cone dystrophy could not be ruled out at that time. Subsequent retesting has been stable to date, but he was permanently grounded because of safety concerns.

2. A 45-year-old navigator/EWO with 3,500 flying hours was diagnosed with adult-onset foveomacular vitelliform dystrophy. This defect began much earlier in life, but wasn't uncovered until he developed a loss of visual acuity O.D. because color plates and FALANT did not identify his acquired B/Y defect. A thorough evaluation revealed a moderate tritan (B/Y) color defect, most likely associated with the foveomacular vitelliform dystrophy. Since current screening tests only detect R/G defects, the EWO was able to pass the current standard PIP and FALANT tests. His defect was regarded to be operationally significant, however, because current color-enhanced radar uses B/Y symbology.

3. An F-4 pilot was performing clear-weather, night touch-and-go's during airfield aircraft carrier landing practice prior to transitioning to carrier duty. Two other aircraft were in a 2-ship formation in an authorized pattern above the airfield and operating on a different radio frequency than the F-4 pilot, as was customary. The F-4 pilot was departing from the airfield when he observed diverging aircraft wingtip lights. He believed the lights to be from one aircraft instead of two and, since they were diverging, he perceived the aircraft to be on a collision vector. He responded by cutting back power to avoid a perceived impending collision, resulting in an unrecoverable stall. Both crewmembers safely ejected; the F-4 was destroyed. The investigation board determined that the F-4 pilot was never in danger of a collision and that the other aircraft were properly positioned and not at fault. The mishap pilot admitted that he had a longstanding color vision deficit and was never able to discriminate between the different colored lights on aircraft wingtips! He had failed the FALANT on initial flight physical exam, but "passed" on retesting. He stated that he was able to pass the color tests only by cheating. Following the mishap, he failed the FALANT test. After further evaluation, he was found to have a congenital deuteranomalous defect. The investigation board determined

that his color vision deficit was a contributing factor because he could not discriminate between different colored wingtip lights, leading to the misperception that there was one aircraft on a collision course in the night sky instead of two separating aircraft in a normal approach pattern.

Current color screening methodology is primarily based on the historical requirement of red/green/white discrimination within a male population and, to a degree, is based on incomplete and faultily-derived information. Retesting for R/G deficiencies at increasingly infrequent intervals--or at all--does not incorporate the capability to survey for acquired color deficiencies. Infrequent monitoring for change, as well as creative testing techniques (often with the direct help of a sympathetic test examiner or "color assistant" who may indirectly be coaxed to provide additional hints), contributes to a less than perfect color screening methodology. Similarly, initial testing results, obtained once, are often historically referenced in an aviator's record without retesting or considering acquired change.

Screening efforts, therefore, have been directed toward identifying those individuals who would be unable to differentiate operationally between red, green and white lights. The incidence of sex-linked congenital defects in the male population has been assessed at 8-9%. This figure can be further broken down into deuteranomaly at 5-6% (green-cone-weak anomalous trichromat); protanomaly at 1% (red-cone-weak anomalous trichromat); deuteranopia at 1% (green-cone-absent dichromat); and protanopia at 1% (red-cone-absent dichromat).

The incidence in the female population is not as well established but is estimated to be almost 0.1-0.3%. Color performance in females has been grossly overlooked because of the inherent and disproportionate nature of the sex-linked association in males, the primary aircrew pool in the past. The incidence of B/Y or tritan defects is regarded to be quite low, in the range of 0.002-.007% of males. The exact incidence of B/Y defects within the male population is unknown and should be regarded falsely low for a variety of reasons, including the fact that B/Y defects are not routinely screened for by common color screening tests. Even the fundamental research by W. E. Wright, who screened for B/Y defects via a B/Y test plate produced in LIFE magazine (British) in 1970, was wrought with considerable underreporting biases. Even less is known about B/Y defects in females. The sex-linked nature of B/Y defects has not been established, appearing to be a more autosomal deficit, and therefore as likely to express itself in the female population as in the male.

Acquired color vision deficits can be produced by a number of pathophysiological mechanisms. These include primary retinal diseases such as idiopathic central serous chorioretinopathy, retinitis pigmentosa, hereditary and acquired maculopathies, glaucoma, optic neuritis, toxic forms and drug-induced forms. For example, antimalarials have been linked to acquired color vision defects. The onset of acquired defects is not always preceded by a decrease in visual acuity or other performance decrement that would alert either the aircrew member or the flight surgeon. These differences can be used clinically to help ascertain the potential etiology of a color vision defect, especially in the absence of historical test scores.

Table 2 summarizes the characteristics of congenital versus acquired color vision defects.

TABLE 2.

CONGENITAL DEFECTS	ACQUIRED DEFECTS
Color loss in specific spectral region	Often no clear-cut area of discrimination loss
Less marked dependence of CV* on target size and illuminance	Marked dependence of CV on target size and illuminance
Characteristic results obtained on various clinical CV tests	Conflicting or variable results on clinical CV tests
Many object colors are named correctly or predictable errors are made	Some object colors are named incorrectly
Both eyes equally affected	Eyes affected asymmetrically
Usually no other visual complaint	May have decreased acuity and field loss
Defect is stable	Defect is labile, with progression and regression

*CV = color vision

It is particularly relevant aeromedically to realize that current selective waveband filters, ranging from the high-contrast yellow visor to the more deeply pigmented dye formulations used in LEP devices, ironically induce complex color vision deficits in color-normal individuals that closely parallel acquired defects such as are seen in ocular or optic nerve disease. These devices induce complex and profound R/G and B/Y color deficits in known color-normals, but are unpredictable and have as yet undetermined impact on color-weak or frankly color-abnormal aircrew. When you overlay significant induced color loss with full visual spectral electronic displays, in the absence of any color-neutral, "see it no matter what" design redundancies, you have created a potential formula for disaster in color-normals and almost certainly in color-abnormals.

At least one midair collision between aircraft engaged in air-to-air training was attributed to factors induced by a combination of yellow visor and green sunglasses worn by the attacking pilot.

III. COLOR TESTS AND METHODOLOGY

<u>R/G Testing</u>. Common test devices and methodology fall into four basic categories: plate, arrangement, lantern, and anomaloscopic tests.

Plate tests depend on confusion lines to elicit their effects. They require the proper color temperature illuminant; otherwise, the basic design premise of the test is invalidated and the results become erroneous. The PIP rely on identification of a colored symbol embedded in a color-confusion or gray back-ground; the background and symbol are composed of confusion colors that appear clearly to color-normals but seem identical (confused) to color-defectives. These screening tests identify those individuals with congenital R/G color defects and are based either on theoretical properties of the color vision system, or on statistical data about confusion colors from known color-defectives. Protanopes confuse certain greens with reds, and deuteranopes confuse other greens with purple. Examples of such tests are the Ishihara, Dvorine, AO, Richmond, AO Hardy-Rand-Rittler, and Tokyo Medical College. Advantages of these tests are they are simple, easy to administer and inexpensive, and can be used with illiterates and young children. The tests generally do well compared with the anomaloscope, showing agreement ranges of 0.95 or higher. No calibration is required by the user. Disadvantages are the required use of a special illuminant C; the presentation of confusion colors, which may be difficult to duplicate through the printing process; and, because of eye pigmentation or lens coloration, the selected colors may not be correct for a specific individual. The plates may be degraded by fingerprints, dust, and excessive light exposure, and must be kept in a case when not in use. The test should be presented monocularly. The plates should also have their order rearranged to preclude sequence memorization that can be shared between test subjects.

Arrangement tests require the subject to arrange color samples by similarity in a series, often a color circle. The caps are numbered on the back and can be moved freely during testing. Several testing strategies are available and include color confusion, hue discrimination, and evaluation of neutral zones (colors seen as gray). Examples of these tests are the FM-100 (hue discrimination), D-15 (color confusion), desaturated D-15 (color confusion), and the Lanthony New Color Test (color confusion and neutral zones). Advantages of these tests are that they are easy to administer and can be used with naive subjects. The FM-100 and D-15 discriminate between protan, deutan and tritan defects, based on axes of confusion. The D-15 does not discriminate anomalous trichromats. The FM-100 is quantitative, with a long history of use and population bases for comparisons in hereditary and acquired conditions. The validity of the tests varies; the D-15 shows agreements with the anomaloscope of between 0.73-1.00. The desaturated D-15 has not accumulated enough data to allow appropriate comparisons. However, 98% of dichromats and 70% of anomalous trichromats will fail the desaturated test. The FM-100 may be statistically assessed at $P<0.05$ or 0.01. Scores may vary with age, test experience, and wavelength discrimination function. The Lanthony test is still under evaluation. It is designed for acquired defects and, therefore, a plethora of test conditions must be considered. All of these tests require manual dexterity and may be difficult for some patients. Pigments may be damaged by fingerprints; therefore, gloves should be worn by test subjects. Spectral quality of the light source illuminating the plates is critical; the caps of the D-15 and FM-100 tests are made from Munsell colors for which CIE specification is available only under illuminant C. No calibration is required.

Lantern tests were conceived as occupational tests to evaluate red/green/white discrimination in seamen, railway personnel, and airline pilots, in order to assess their ability to discriminate navigation aids and signals. Correct color recognition is the important variable. The value of lantern tests is their ability to simulate the actual work environment. They do not specifically identify types of color defects. They were designed to screen out individuals who cannot see red, green and white occupationally, and will pass color-normals and color-weak R/G defectives. The expectation is that color defectives who pass a lantern test will perform as well as color-normals in their occupation. The most representative device, and the only one readily available, is the FALANT. This test uses red, green and white lights that are confused by people with more severe color defects and does not attempt to mimic navigational aids. The assumption is that if an observer can see the lights that color-defectives can't see, then they should certainly see those colors that color-defectives don't fail. A design feature of this test permits 30% of color-defectives to pass. The validity of these tests, compared to the anomaloscope, is very limited, so agreement factors have not been published. Test advantages are the device is self-luminous, so it may be used in normal room light; random presentation is easy to accomplish; and administration and scoring do not require highly trained personnel. Availability varies, being an "off-and-on" phenomenon. Several creative schemes have been devised to "game" this test or "con" the examiner, one example resulting in an aircraft loss. No calibration or maintenance of the lantern is required, and CIE chromaticity specifications are available.

The anomaloscope is the gold standard device of color vision testing and depends on the Rayleigh equation. The test subject is asked to match a yellow light by mixing varying amounts of red and green. The amount of red and green selected is the Rayleigh result. Normals match pure yellow (589 nm) with an equal mixture of pure red (670 nm) and green (545 nm). Protanomalous trichromats require more red in the mixture and deuteranomalous trichromats more green to make up for their inherent deficiencies in a particular cone class. Protanopic or deuteranopic dichromats will accept a wide range of R/G mixtures to "match" yellow, because they match brightness and not color. This test has a long and well-established history and is the definitive test for R/G color vision. It is used to validate other color vision tests and requires a spectroscope for calibration. The apparatus is expensive, requires experienced examiner skills, will not tolerate rough handling, and is not a readily available screening tool. The Nagel anomaloscope is the only device that may be used to classify genetic R/G color vision defects. Several new electronic versions that include B/Y testing are currently available and under evaluation.

Plate and arrangement tests are designed to identify individuals who may need more extensive color testing. They do not diagnose a specific color defect. A test subject who passes the plate test for R/G deficits is regarded as color-normal for R/G only. Plate tests are not quantitative but should be regarded as pass/fail, requiring further evaluation with other sophisticated testing to evaluate the color deficit. Individual laboratories need to establish their own test battery to satisfy their needs with respect to R/G defectives. A validated plate test and the FALANT are both effective R/G screeners. In combination, they even improve upon their validity as opposed to one test employed alone.

B/Y Testing. Because of the apparent significantly lower incidence of congenital B/Y defectives and the traditional R/G aviation world, current color screening methodology excludes this category. Of questionable historical validity, we believe that this is no longer the case, and therefore B/Y should be evaluated as well, for screening congenital and acquired deficiencies. We maintain that, in the modern cockpit of today and tomorrow, the importance of B/Y discrimination has been underscored and needs consideration in order to maximize this aspect of the aviator's visual system. Given the complicated induced color defects imposed with LEP, extremely task-saturated multispectral electronic displays, and the need to avoid limiting design evolution that could capitalize on the virtues of a truly color-normal visual system, we believe it is time to screen and monitor for B/Y defects. Several tests currently are available to assess this ability; however, many remain elusive and, at the present time, are not readily available. This is not to say that, with proper support, they could not become so. Certainly, the FM-100 and D-15 evaluate this performance element; however, they are not ideal screeners. These tests were not optimized to assess this performance and do not identify severe anomalous trichromats. The Pickford-Nicolson anomaloscope and the AO Hardy-Rand-Rittler PIP are no longer available commercially, but were employed in the past to assess B/Y deficits. The Farnsworth F2 plate remains available on a limited basis to color researchers, but could easily be made more available as a screening plate. It can be produced inexpensively and could be included in the standard PIP test to allow screening for B/Y defects. Failing this test would be either disqualifying or indicate further definitive evaluation. The F2 plate is currently available through the Naval Submarine Medical Research Laboratory, Groton, Connecticut.

If our color logic is acceptable, adding the Farnsworth F2 plate would provide a more optimal screening strategy. If acquisition of this type of plate fails, then the D-15 could be employed. Although somewhat more time-consuming and perhaps more redundant, the D-15 will test for B/Y dichromats but not for B/Y trichromats; it's therefore less than perfect for this purpose.

Development of a standard PIP Part 2 test offers potentially a cost-effective alternative to the F2 plate. This test was developed in 1983, basically as an acquired B/Y color-vision tester, but has not so far been employed as a screening test because of our fundamental approach concentrating on R/G deficits. It is readily available, inexpensive ($57 U.S., Igaku-Shoin Ltd, 1 Madison Ave, New York 10010), and designed to identify acquired B/Y deficits. Its ability to identify congenital B/Y deficits warrants further investigation and may offer an effective alternative to the F2 once validated from this perspective in the future. In the meantime, it is an effective evaluation tool in the evaluation of B/Y deficiency.

A more expensive approach would be to design an operational color screening cockpit employing all the latest electronic displays in a real-world simulation test. Obviously, standardization of display symbology would facilitate this process, but may be unrealistic operationally. Certainly an effective and practical compromise could eventually be reached. Fundamentally, and in the meantime, we believe that inexpensive testing methodologies to locate "Super Coneman" currently exist.

IV. MODERN AVIATION COLOR VISION ISSUES

It is appropriate to expand consideration of color vision issues into the arena of the modern cockpit and beyond, in the hope of stimulating imaginations and concerns in support of more complete and stringent color testing. One has to only look back 20 years in cockpit design to compare current "old" operational aircraft with "new" aircraft to appreciate the way in which cockpit designs are evolving. A valid question--painful for some--might be "Will the manned part of the system evolve with it?"

<u>Selective waveband filters.</u> The all-glass cockpit produces a staggering amount of predominantly color-coded visual information for artistic, if not functional, reasons. Redundant symbology and consideration of the impact of selective waveband filters on discriminating this symbology have either been totally excluded, partially accommodated, or realized after the fact. Clearly, red, green and white signals have become passe and boring. Current electronic displays employ a vast color palette, seemingly attempting to use as many pixels of individual colors as possible. Considering the eye can recognize 4,000 individual colors, the possibilities are endless. All this colormania has been done without regard for color-defectives. In fact, an aviator had better be a "Super Coneman" to fully appreciate the electronic, multidimensional, full-spectrum, technicolor extravaganza in the cockpit. When LEP enters the picture operationally, things unintentionally begin disappearing from this visual environment. Certain colored symbology sizes become difficult to see through LEP visors, requiring doubling their size to ensure 100% recognition. Redundant, color-independent symbology is not always present, but, without doubt, should be. For the "operationally induced" color-impaired, it is imperative that "switchology" exist on current displays to neutralize the impact of LEP, but such design features complicate and add to the cost of the equipment. However, there appears to be no alternative if we are to adequately protect our aircrew from laser threats. Since hostile lasers remain agile with respect to wavelength and a single defensive solution elusive, this compromise of color performance is likely to remain an irritating cost of doing business. Fundamentally, in order to predict the impact of a particular LEP on an aviator, it is beneficial for vision

scientists and engineers to understand the impact of a particular visor on the aircrew population. There is no question that the impact on color-normals is profound. The inclusion of color-weak or color-abnormal aviators within this population and the lack of information to date on the impact of these devices on this subset, complicates this matter considerably. In addition to an unpredictable effect on those aircrew, it requires complicated studies to ascertain the full extent of such devices on color-abnormals. Thus, there remains the seemingly insurmountable task of protecting aircrew from agile laser threats and still ensuring the unaltered full potential of information transfer through existing and future aircraft. A laser-induced reality may require a return to monochromatic displays or removing the pilot. Some aircraft employ color contour map-display systems that are presented visually to aircrew through various means. These displays must be modified to accommodate or neutralize the impact of LEP on the information they present. Since only one visor can be worn at a time, it is a challenge to match the appropriate visor to the threat environment. Given agile laser threats, it is likely that this selection will more likely be wrong than right. We can only hope that evolving technologies will solve this problem.

Air-to-Ground Operations. Despite exclusive initial night strikes using night-vision devices (NVDs), Desert Storm demonstrated that surgical daylight strikes continued to be--and are likely to be more so in the future--a prominent part of tactical air operations. In this context, map reading tasks, visual target confirmation, and smoke marker detection are greatly enhanced by, if not totally dependent upon, an intact color vision system. These tasks become extremely difficult, if not impossible, through LEP devices, and have a variable impact on color-normals and an unpredictable one on color-abnormals. Although some selective waveband filters can enhance detection of a particular color range, this advantage is accompanied by a loss of discriminatory ability in other color ranges and an overall reduction of luminance, inducing a new challenge. This new, altered color world would have to be "learned" rapidly, often under duress; information processing time would be increased and a color-weak individual's performance time would be degraded disproportionately.

Naval air operations present additional unique and critical color-recognition tasks. These tasks require exquisite choreography between aircrew and deck crew who wear color-coded ensembles to identify their flight deck responsibilities. Extremely hazardous, time-critical night carrier landings, although not totally dependent on color discrimination because of automatic landing light systems, are greatly improved by the aviator's ability to discriminate color cues rapidly. Colored lights are important to delineate aircraft carrier superstructure and orientation during night recoveries. This is not to say that night landings cannot be accomplished by color-weak individuals, but this extremely critical phase of flight, characterized by a very narrow window of opportunity and a paucity of alternatives, is greatly enhanced by intact color discrimination.

Air-to-Air Operations. Despite technological advances in long-range missile intercepts, visual identification of potential hostile aircraft in politically sensitive situations, and the fact that not all missiles hit their intended target (only 20% in actual combat) still dictate the need for close-range dog-fighting capability with its strong reliance on the aircraft's cannon. The tactical offensive employment of airborne lasers to dazzle or incapacitate an adversary requires the dependence on LEP in the air-to-air arena in the future. A pilot's ability to discriminate adversarial aircraft close in against varying color contrasts despite creative camouflage schemes make this task even more difficult through LEP. In some cases, neutral gray aircraft against a low-contrast surround appear invisible through certain visors, not to mention that they are extremely difficult to see with the naked eye alone. Recent military operations have been critically linked to successful day and night refueling operations. Although a tanker's refueling light tracks employ redundant symbology and only red, green and white lights, blue basket markings on certain aircraft add another dimension. Throw in a requirement for LEP because of the proximity of hostilities to refueling operations and the fatigue from repetitive night taskings, and it can be quickly appreciated how color serves to reduce the stress and difficulty associated with such tasks.

Night Vision Devices (NVDs). The integration of NVDs in air operations has introduced a plethora of new physiologic and equipment interface issues. In effect, NVDs may be thought of in the context of biologic coupling, introducing a complex blend of aerovisual and engineering factors. A great deal has been written regarding the use of NVDs by aircrew; however, we still are relatively naive in such issues as NVD performance nomograms and visual standards, the impact of NVD performance as a function of ocular pathology, physiologic/optical interphasing and other essential NVD neurobiological coupling issues such as color perception. At present, the performance of aircrew with NVDs with respect to an underlying color deficiency has not been evaluated, although studies have been proposed. The emission maximum for the generic night vision goggles (NVG) is 530 nm; the wavelength maximums for red and green cones are 546 and 571 nm, respectively. Thus, it appears that neither cone system is optimally stimulated and can be concluded that the chromatic system is not well coupled to these devices. It seems intuitive that engineering a phosphor's emission characteristics to match the retinal sensitivity of the operator is simpler than any other proposed solution. The impact of any existing color deficiency, be it congenital or acquired, on an individual's ability to optimally use NVDs remains undetermined. As greater reliance is placed on NVDs, better neurobiologic coupling in color-normal individuals is required, and standards must be determined for color-weak individuals to ensure there is no performance degradation with these severely visual-tasking devices. This issue raises a potential disconnect to be avoided or engineered out of the system until studies permit a better understanding of NVD color coupling in color-normals and color-weak/abnormals. How much simpler it would be to establish one category of super aviator, "Super Coneman", and neurobiologically couple the NVD without having to consider a multitude of biological subsets in the process.

Chromatic Contrast. The detection of sharp edges in a vernier acuity task (hyperacuity) has traditionally been thought to be a product of the luminance system. It is now known to be influenced by color. In a simple situation, suppose two green bars in a red surround provide a vernier (offset) target. If the bars are isoluminant (brightness match), there is a 70% chromatically determined loss of acuity. These sorts of spatial-chromatic interactions must be understood and exploited in the cockpit. Traditional contrast sensitivity, used to accurately evaluate pattern vision, principally uses the brightness pathway. Homochromatic, isoluminant gratings (e.g., alternating red and red stripes) have no visible boundaries. Heterochromatic, isoluminant gratings (alternating red and green stripes) have boundaries that may only arise from the chromatic system, because there is no luminance difference; that is, there is chromatic contrast. This observation has created a new research area relevant to display technology and other aspects of color perception. Luminance patterns and chromatic patterns interact in several ways. Two major effects occur: facilitation and attenuation. The interactions are spatial frequency and wavelength dependent. These sorts of data begin to approximate the real world (cockpit). There is further evidence to support the notion that spatial localization is dependent upon color and luminance contrast. Color can support binocular fusion and color targets may be fused in the context of rivalrous luminance information, just as luminance contrast targets may be fused in the presence of rivalrous color information. Finally, stereopsis for chromatic contrast targets can be eliminated with suitable luminance contrast. Clearly, stereopsis may be manipulated, enhanced, masked, attenuated, etc., resulting in a range of control of stereopsis that heretofore has not been possible. This concept can be regarded as synthetic stereopsis. This manipulation, optimally intended to alter, highlight, attenuate or illuminate information presented in the cockpit, may play a role in future cockpits, especially if virtual reality continues to evolve. It will greatly enhance engineering development and the predicted impact from this type of technology if the pool of aviators share a common and intact normal color visual system. The process of understanding spatial chromatic interactions has just begun and deserves serious attention in those situations that involve biologic coupling of the aviator with cockpit displays, especially in hostile environments that seem to argue for a virtual cockpit approach.

Virtual Reality. One proposed solution to the agile threat environment in future air operations is virtual reality. It seems impossible to protect aircrew and harden assorted optical sensors from all the illusive and dynamic laser threats. "Virtually impossible solution + emerging realities = virtual reality." Although reactive canopies and visors may play a role, the threat environment is so rich and includes so many other threat wavelengths that virtual reality cockpits propose a valid approach to minimizing the impact of such threats. This is an exceedingly complex challenge, and new physiologic problems will certainly arise as this technology matures and is integrated into weapon systems. Nonetheless, there appear to be significant benefits associated with this approach. An alternative solution proposes removal of the biological component of the weapon system altogether, but for the foreseeable future, this would be regarded as an unrealistic approach, unappealing to enthusiasts, even if predicated on fertile technical merit. The ability to exploit color physics and physiological issues is bounded only by imagination and biological limitations. Ideally, freelance engineering without the encumbrances of limitations secondary to color vision deficits fundamentally and logically warrants support. Should a potential technological development in this area be subjected to premature demise from unnecessary physiological handicaps? Or not developed because of an unpredictable impact when coupled biologically? It seems scientifically unfair to penalize creativity by having to deal with less than optimum human visual systems. "Super Coneman" would be free to conquer his "Color Metropolis" unencumbered by any kryptonite-like weaknesses. Synthetic stereopsis, color contrast, and color stereopsis are some of the emerging color vision principles that need to be fully exploited in the virtual realm before being discarded or lost.

Color Testing Realities. Assessment of an aviator's color performance has often been compromised by basic breaches of testing principles. For example, the wrong illuminant invalidates plate and arrangement tests and contributes to a potentially erroneous passing score. This error, or any initially acquired faulty information, is compounded in the absence of or infrequent requirement for reassessing this performance. Dependence upon a historically referenced, previously passed qualifying test forgoes the possibility of validation and monitoring for acquired color deficiencies and inappropriately commits a prospective aviator into an ever-increasingly complex color world. Retesting policy regarding color performance varies and often a historically referenced test score suffices in lieu of retesting. Creative gaming techniques, to include memorization, sharing answers, and more elaborate schema to assure a passing score, have all been employed successfully in the past. An example of an aircraft lost to this phenomenon was given earlier. It is not good policy for the aerovisual scientist to be adversarial to prospective and trained aviators, but it is our responsibility to ensure that tests are administered properly and that we eliminate those candidates that are likely to be visually compromised. The "color assistant" phenomenon during color testing runs the full spectrum, from outright sympathetic data entry to compromised testing technique to disinterest or lack of understanding of the significance of responses.

Regardless, performance assessments based on erroneous information can be improperly carried throughout an aviator's career. Acquired color deficiencies can be elusive and are not always associated with other warning signs such as reduced acuity. Reducing the routine monitoring requirement is therefore fundamentally flawed and does not identify an impaired aviator within the color-task-saturated environment of today's and tomorrow's aircraft.

V. SUPERCONEMAN

It appears, given both real and perhaps some conjectural issues, that the argument supporting the search for "Super Coneman" exists now and will have only greater relevance in the future, assuming that humans continue to be coupled with aircraft. The fact is that "Super Coneman" exists now; he's called color-normal. The color world is polydimensional, but our current mode of testing color is based on a unidimensional approach. There are interactions between the chromatic spatial system and the achromatic spatial system such that screening for color capability alone may be misleading in terms of occupational needs and standards, often the basis for color tests in the past. Color anomalies have only been marginally linked to actual "real-world" color performance, and better delineation seems necessary. The color world of the future will need to be understood in the context of interactions of the color system with other aspects of vision, to capitalize on emerging technologies and future cockpits.

Two alternative approaches are possible: one is to promote more extensive screening for preexisting color pathology, coupled with frequent reevaluation, and the other is to continue business as usual and minimize the impact of color-related tasking. The former can be accomplished by more comprehensive visual screening, to include B/Y assessment, whereas the latter accepts a handicap and requires engineered color-independent solutions. The impact of color can be minimized in displays by programming and designing in a switchable, color-neutral mode to employ redundant symbology visible through any present and future LEP or filters, or to maintain a color-neutral approach (in essence a return to black and white electronic displays) wherever possible. Perhaps the ultimate expression of this approach would be to design us completely out of the cockpit, or in the meantime, optimize the biological coupling between display design and known color issues and to embrace color-defectives as well. The first approach maximizes the impact of color discrimination by advocating stricter color standards ("Super Coneman"), and maximizes exploitation of emerging color technologies such as synthetic stereopsis, chromatic contrast and other enhancements yet to evolve. The feasibility of embracing a more stringent approach can be done effectively and with acceptable cost, especially if candidate screening is only accomplished at several centers.

Plate and arrangement tests are designed to simply screen individuals who may need more extensive color testing. Adding to existing plate or lantern methods the ability to assess B/Y performance and to support a program of more frequent testing, supported by appropriate disqualification regulations, will ensure a color-normal aviator pool--one that will have a predictable impact from today's and tomorrow's optical devices and aids--that correlates with laboratory studies and predictably extrapolates to the entire flying pool. This pool would facilitate engineering options and biologic coupling. It would be a pool whose visual tasks and cockpit performance would be enhanced by the color vision system and not penalized by it, thereby negating effective use of that information during a critical phase of flight.

In the final analysis, individual countries will establish an appropriate battery of tests to satisfy their needs. Political realities, however, may alter a pure approach. Today's world of kaleidoscopic color cockpits and tasks, overshadowed by a military drawdown and pilot reductions, seems to echo an opportunity to reduce the pool of candidates to only the very best, in this case, "Super Coneman". This approach will ensure that, to the limits of our ability, we optimally, perhaps synergistically, couple the biologic component to the airframe well into the 21st century, or at least for as long as we continue to sit on a rocket, racing through space, with our hair on fire.

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