

Occupational Vision Standards: A Review

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1.0 Introduction

Effective aircraft maintenance inspection requires non-destructive inspection and testing (NDI/NDT) personnel to be experienced, skilled, and able. The present certification and qualification process requires applicants to pass written and practical examinations in order to demonstrate that they are qualified to carry out specific NDT methods. Currently no common standard exists in the aviation industry for the visual qualifications of inspectors; however, various airlines and aircraft maintenance facilities have developed their own respective vision qualification programs. This highlights the need for a uniform and universally accepted set of vision standards that would apply to all aircraft NDI/NDT personnel.

This report was commissioned by the Federal Aviation Administration (FAA) to partially fulfill FAA Aviation Maintenance Requirement 193, which calls for *Vision Testing Requirements for Certain Persons Maintaining and Inspecting Aircraft and Aircraft Components*. In collaboration with the FAA, NASA has proposed a research plan designed to specify visual needs in relation to specific occupational tasks of aviation maintenance workers and inspectors. As a first step this literature review is being performed to identify and summarize published research relevant to setting occupational vision standards for NDI/NDT personnel.

The following review is a compilation of a text and WEB-based search for occupational vision requirements, knowledge gained from site visits to major aircraft maintenance facilities, relevant information from aviation technical, mechanical, and inspection textbooks, the FAA maintenance human factors web-site¹, and the human vision literature. A principal intent of this literature review is to gather current knowledge about aircraft inspection and human vision, combined with current vision standards required for various other occupations, in preparation for establishing vision standards for specific NDI and visual inspection tasks.

One question that arises is whether standards used in other “Materials Evaluation” occupations can be borrowed for aircraft inspection. Certification programs that include vision requirements have been written by organizations such as the military, welders, and mechanical engineers. Here we will discuss such standards and their applicability to the vision demands in aircraft inspection.

Optimally, this literature review would follow a thorough vision task analysis for NDI and visual inspection. Although task analysis and descriptions have been performed on aircraft maintenance inspection (Gramopadhye & Kelkar, 1999), these analyses have not focused on the role of visual processes: thus, a more detailed analysis is needed to verify visual task demands. The list of visual functions described below is not based on a rigorously obtained taxonomy, but instead is based on observations made at aviation maintenance facilities by the authors during site visits.

This report is divided into four main sections. The first section describes the FAA requirement calling for vision standards for NDI/NDT inspectors. We then discuss NDI/NDT basic training, tasks and associated visual needs and provide an overview of

¹ <http://hfskyway.faa.gov>



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field observations taken by the authors of this report. Section 2.0 excerpts the visual perception literature as it pertains to setting visual requirements. It will be shown that the tools to predict real-world performance are just now reaching maturity. This section also outlines current vision standards for several vision-intensive occupations² and whether these standards were empirically derived, based on expert opinion, or borrowed from other occupations. We then discuss to what extent these standards can be applied to aviation maintenance inspection. In Section 3.0 recommendations are provided for vision standards that specifically relate to the vision needs of NDI/NDT inspectors. In conclusion we recommend that current vision standards written for other occupations cannot be directly adopted when writing aircraft inspection vision standards since the tasks performed by different occupations differ substantially from aviation maintenance inspection tasks. Additionally, most occupational vision standards are not empirically substantiated and appear to be arbitrarily decided.

1.1 Background

FAA Requirement 193 states that the Project, at a minimum, will determine standards for near visual acuity, distance visual acuity, and color perception for aircraft maintenance inspectors. In September of 2001 the FAA produced a memorandum outlining the vision requirements for NDT inspection personnel and stated that these requirements could “be used to establish if personnel performing NDT inspections are qualified” (Paskiewicz/FAA Memorandum 9/26/01). NDT personnel meeting the requirements of having natural or corrected near visual acuity in one or both eyes of at least Jaeger #1 or the equivalent (20/20) and demonstrating the ability to differentiate colors used in the NDT methods for which they are certified are considered to be visually “qualified”. This memorandum followed an FAA Advisory Circular (AC No: 65-31) in October of 2001. The vision requirements are similar to the memorandum; however, the Advisory Circular goes on to state that visual acuity needs to be reevaluated yearly.

The FAA vision standards are basically identical to other industry and military vision standards such as the Aerospace Industries Associations’ (AIA NAS-410), the Society of Automotive Engineers (AS7114), the Navy’s (NAVSEA T9074-AS-GIB-010/271), the American National Standards Institute (ANSI/ASNT CP-189-2001) and the British Institute of Non-Destructive Testing (PSL/44). Two older and commonly referenced NDT standards documents have been updated; AIA standard NAS-410 supersedes MIL-ST-410 and the Navy’s NAVSEA standards document supersedes MIL-STD-271F. (Appendix A)

One of the most recently published standards documents for NDT personnel is the Air Transport Associations’ Specification 105 (ATA 105). It recommends a near visual acuity standard of 20/25 and is one of the few organizations that provide a distance visual acuity standard, which is 20/50. (Appendix B) The color standard remains similar to the other previously mentioned documents and the FAA’s Advisory Circular. (Appendix C) Other organizations found to provide distance visual acuity standards for NDT inspectors are the American Welding Society (AWS D1.1/D1.1M: 2002), which requires distance

² For a more thorough review of published occupational vision standards see the Association of Optometrists’ (the AOP is based in London) Vision Standards Handbook, which can be obtained from <http://www.assoc-optometrists.org/>.



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acuity of at least 20/40, but does not clearly define the near visual acuity standard, and the American Society of Mechanical Engineers' 2001 ASME Boiler & Pressure Vessel Code (IMA-2321), which requires a distance acuity of 20/30 in addition to a near acuity standard of 20/25 and a color vision requirement. Many employers assume that the correction of a worker's refractive error alone is adequate to ensure safe and effective performance on visually demanding tasks. The FAA is interested in developing a performance-based vision standard relevant to all NDI/NDT techniques. The newly formed standards would reflect the actual visual needs for specific tasks performed by the inspector. NASA has proposed a research plan designed to specify visual needs in relation to specific occupational tasks. The proposed research will establish empirically sound standards for visual acuity and color vision; additionally, a broader array of visual parameters may be included if it is determined that they are necessary for adequate task performance. Example parameters include, but are not limited to, depth perception/stereo acuity, peripheral vision and contrast sensitivity.

1.2 The Use of Vision in Aircraft Maintenance Inspection

Aircraft inspection is a complex process, requiring many tasks, skills, and procedures. Many tasks are performed in the safe environment of a maintenance workshop facility while others are performed amid potentially hazardous ramp operations. Vision is a fundamental component of effective aircraft maintenance inspection.³ Not only does "good" vision ensure that inspectors can better detect airframe and engine component flaws, but good vision is imperative in keeping an inspector and coworkers out of harms way.

Visual inspection represents approximately 80% of all aviation maintenance inspection tasks (Goranson & Rogers, 1983). Its main purpose is the detection of discontinuities⁴ such as cracks⁵ and corrosion⁶ within the airframe and powerplant regions of the aircraft. Other visually detectable defects include component wear, chafed electrical wiring, delamination of composites, buckled or bulging skin, and damage due to the environment, accidents, overheating, and lightning strikes.

Significant cracks and corrosion are often subtle or not visible to the naked eye; for this reason inspectors often use visual aids such as bright flashlights, mirrors, laryngoscopes, and magnifying glasses to increase defect visibility. Borescopes are regularly used to examine inaccessible areas such as the interior of aircraft engines or hidden airframe

³ Although vision is important, so too are other cognitive factors such as attention. In addition, inspectors are knowledgeable about individual components as well as the overall aircraft being inspected, thus they possess the background to properly locate, identify, and evaluate aircraft defects.

⁴ A discontinuity may be defined as "spatially sharp departures from material homogeneity and continuity inside a component at any level of magnification" (Hellier, 2001).

⁵ A crack may be defined as "A planar breach in continuity in a material" (Hellier, 2001). They are typically caused by two surfaces being overlaid at a boundary.

⁶ Corrosion may be defined as "the electrochemical degradation of metallic materials". (Hellier, 2001).



sections for structural defects such as pitting, scoring, tool marks, cracked cylinders, and seal and gasket irregularities.

1.3 Site Visits: Interviews and Field Observations

This literature review was conducted in association with aviation industry partners to ensure its applicability to the setting of vision standards for maintenance inspectors. NDI inspectors and training supervisors were interviewed; furthermore, field observations of experienced inspectors were made, revealing a number of visual processes that appear to be relevant to NDI and visual inspection. We were able to observe visual inspections, borescope and ultrasonic procedures in addition to the results from florescent penetrant, eddy current, and X-ray procedures.

2.0 Human Visual Processing, Vision Standards, and Relationship to Maintenance Inspection

How will current vision research and our knowledge of human visual processing provide insight into developing standards for aircraft maintenance inspection tasks? This section focuses on laboratory data collected using real-world visual images in order to capture the complexity of the inspection task. In addition, we will discuss the background behind vision standards in various occupations and their applicability to aviation maintenance inspection.

Section 2.0 is organized into five main sections. The first three sections describe psychophysical research related to classical vision requirements; i.e., color vision, near and distance acuity, and peripheral vision. The remaining sections describe research related to visual processes that have not classically been included in occupational vision requirements, but that appear to be highly related to specific tasks performed during aircraft inspection.⁷

2.1 Color Discrimination

2.1.1 Relevant Terms and Basics

Color discrimination is defined as the ability to differentiate between shades of a color or the difference between two or more colors when luminance has been equated or randomized. The factors that influence color discrimination have been described thoroughly (e.g., Kaufman, 1974; Schiff, 1980; Sekuler & Blake, 1990); these sources were used to compile the brief summary of human color vision within this sub-section.

The human retina (a neuro-membrane lining the inside back of the eye) is made up of receptors called rods and cones. When only the rods, densest outside the central retina or macular area, are functioning (i.e., when viewing at low luminance levels), colors are not visibly perceptible. Cones, densest in the central retina, provide the perception of color.

Humans with normal color vision are traditionally regarded as having three cone types, supporting trichromacy, the ability to match colors with three primaries. As shown in the

⁷ Although we have dissected the mechanisms of visual perception into separate processes (e.g., color discrimination, contrast perception, ...), perception is an amalgam of these processes working in harmony.



spectral sensitivity curves in Figure 1, each cone contains a photopigment whose sensitivity peaks at either the short, medium, or long wavelengths (e.g., blue, green, or red).

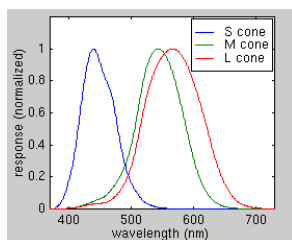


Figure 1. Cone sensitivity plot.

Individuals with inherited color-vision defects have either the complete loss of a photopigment (dichromacy), or a shift in the peak sensitivity of one of the photopigments (anomalous trichromacy), resulting in the decreased ability to discriminate between colors such as red and green. Approximately 8-10% of the men and less than 0.5% of the women in the United States are born with some form of recessive red-green deficit, or “colorblindness” (Haegerström-Portnoy, 1990).

The Ishihara color test is one of several standard color vision tests given by optometrists and ophthalmologists for general and occupational color vision screenings. Figure 2(a) shows one of several Ishihara plates. To appreciate how an individual with a color deficit perceives color, the appearance of an Ishihara plate is simulated for three types of dichromats in Figure 2b-d.

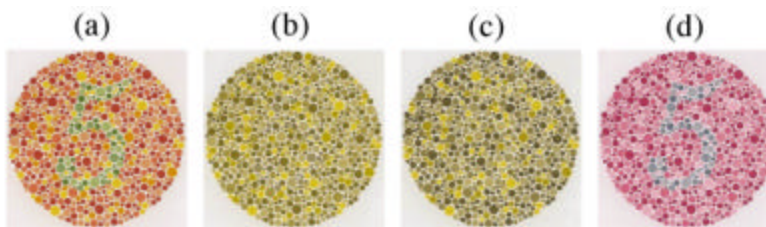


Figure 2. Ishihara Plates. (a) Those with normal color vision should perceive the number “5” embedded in the plate. (b-d) These images are simulations of three types of dichromacy: (b) deuteranope, (c) protanope, and (d) tritanope. Ishihara plates do not measure the severity of color vision loss.

As can be seen in the example above, dichromats have severe color-vision deficits; however, they account for only ~1% of all individuals with a color-vision deficit. The remaining 99% of individuals with an inherited color-vision defect are anomalous trichromats, being either protanomalous (red weak) or deuteranomalous (green weak). The majority of all color defectives are deuteranomalous, with 5% of all males and 0.25% of all females showing this type of deficit (Cline *et al.*, 1989). The ability to discriminate colors for these two groups can range from almost normal to almost dichromatic. Although protanomalous and deuteranomalous people have some difficulty doing tasks that require color vision, many are unaware that their color perception is not normal (Amos, 1998). Some color-anomalous individuals perform better than their color normal peers at certain job tasks. An example from the military is that of individuals with certain specific types of color deficits being able to better identify camouflage colors and patterns.



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Possibly as many individuals have acquired color-vision defects as those with hereditary defects. Most color vision tests screen for red-green color defects, which are the most common hereditary color defect, whereas the majority of acquired color-vision defects are blue-yellow. Acquired defects are most often associated with ocular and systemic disorders such as age-related yellowing of the crystalline lens (cataract), glaucoma, diabetic retinopathy or hypertensive retinopathy. Additionally, many drugs have been documented to induce changes in color perception; examples include tranquilizers, antibiotics, chemotherapeutic drugs, cardiovascular drugs and anti-malarials (Amos, 1998). Environmentally induced forms of color weakness also exist. Exposure to toxic gases (Kilburn, 2000; Dick *et al.*, 2000) and industrial chemicals (Gobba & Cavalleri, 2000; Cavalleri *et al.*, 2000) can induce color vision loss⁸. It is thus imperative to monitor color vision at each ocular examination and not assume that color vision does not change over an individual's lifetime.

2.1.2 Color Discrimination: Real-world Performance Literature, Vision Standards, and Relevance to Aircraft Maintenance Inspection

Psychophysical evidence shows that humans have a high sensitivity to color in natural scenes (Chaparro *et al.*, 1993). Color also helps individuals to segment (Gegenfurtner & Rieger, 2000) and to selectively attend to particular aspects of a scene (Deco & Zihl, 2001).

Extensive research has been performed on the effects of color deficiencies on air traffic controller's (ATC) job performance. Many of the earlier studies involved a small number of color defectives: typically the experience level of the individuals with color defects and those individuals with normal color vision were not equated. Recently large subject pools of color weak individuals without ATC experience have been tested (Mertens, 1990; Mertens & Milburn, 1992a,b; Mertens & Milburn, 1996; Mertens *et al.*, 2000). Typically subjects are tested on simulated ATC tasks such as color coding of flight progress strips, identifying aircraft lights, and reading color weather radars. The results from these studies suggest that protanopes (Adams & Tague, 1985) and deuteranopes (Kuyk *et al.*, 1986, 1987) are often unable to adequately perform ATC tasks. The use of certain colors can slow down object detection or discrimination speed for ATC-related object detection (Mertens *et al.*, 1992b) and general text readability (Legge *et al.*, 1990) in color weak individuals. The potential for an adverse interaction of color-coding with color deficiency must always be considered.

The performance of individuals with color deficits on discrimination and detection tasks has been studied in several other occupations. In the medical realm it has been noted that physicians with color weaknesses may have difficulty interpreting lab tests, evaluating the color of bodily fluids (Iserson, 2001), or recognizing blood in body fluids (Reiss *et al.*, 2001). Task accuracy and speed while using computer displays are significantly affected by color vision deficits in patients with macular degeneration (Scott *et al.*, 2002).

Although a color vision deficiency can be potentially handicapping, color vision and thus color vision deficits have been found to be minor factors in visual search performance at sea (Donderi, 1994) and in automobile driving performance (Owsley & McGwin, 1999).

⁸ For example, toluene exposure in rubber workers, PCE exposed dry-cleaners, and exposure to paint solvents or formaldehyde exposures during home renovations.



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One reason that color may not be a salient variable for some tasks is that the perception of color is often redundant with other salient determiners of attention such as luminance and orientation (Parkhurst *et al.*, 2002).

“Accurate color identification is required for many visual inspection tasks of aircraft and related articles (color-coded electronic wiring and tubing, paint, penetrant and magnetic particle inspection indications, corrosion, safety signs, etc.)” (AC 43-204, 1997) Many airframe and engine defects are identifiable by their color, thus the ability to correctly perceive and identify colors may prove to be significantly important for efficient aircraft inspection. Consistent with the psychophysical literature (Parkhurst *et al.*, 2002), our observations of experienced inspectors suggest that color changes in the aircraft surface, wiring, and within aircraft components are a salient determiner of attentional allocation, indicating that subtle color differences are used for defect detection.

“Most of the defects found on aircraft are found by visual inspections”; the main three types being cracks, disbanding, and corrosion (AC 43-204, 1997). General surface corrosion, the most common form of corrosion, first presents as a dulling of the effected surface; whereas pitting corrosion, one of the most destructive forms of corrosion, is first seen as a white or gray dust-like powdery deposit (AC 43.13-1B, 1998). However, a few forms of corrosion can be described by a variety of colors depending on the composite material on which the corrosion has formed. Corrosion on copper produces a blue to blue-green powdery deposit, silver plated copper will produce brown-red deposits when the copper becomes exposed and nickel-based metals can produce green powdery deposits when corrosion is present (AC 43-4A, 1991). Detection of uniform etch corrosion is likely a combination of color discrimination, contrast perception, and texture discrimination. Pitting corrosion, on the other hand, is likely a combination of contrast perception (e.g., white or gray powdery deposit) and texture discrimination – not involving the perception of color. Corrosion can be rust colored, a cue not as salient to anomalous trichromats or dichromats as to color normal trichromats. However, there are many variations of color weakness; therefore, knowledge about the extent of color loss is required to definitively say whether an inspector should be excluded from performing certain types of task or from being completely excluded from the job. Research is needed to identify the degree and range of color weakness that is acceptable for NDI inspection of aircraft.

The following is a partial list of tasks performed by the NDI inspector (and the typical inspection technique) that may require color discrimination abilities

- discriminating paint colors (visual & borescope)
- lightning strikes (visual)
- corrosion detection (visual)
- discoloration from overheating (visual)
- zonal inspections in cabin (visual - see green)
- cracks (visual & florescent penetrant)
- sulfidation (visual & borescope - dark greenish- gray in hot section of engine, low pressure turbine)



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A few studies have been conducted to empirically substantiate the color vision standards within the Air Force (Tredici *et al.*, 1972) and Coast Guard (Donderi, 1994), while the color vision standard for air traffic controllers has been studied extensively (Mertens, 1990; Mertens & Milburn, 1992; Mertens & Milburn, 1996). However, the majority of vision standards for various occupations have not originated from empirical testing, but instead from expert opinion or the standards have been borrowed from other occupations. Due to the lack of standardization of visual requirements, many occupations such as police and firefighters have a broad range of color vision standards depending on the state or city in which a department is located. (U.S. Department of the Interior, 2002; Grand Junction, Colorado Firefighter web site; Virginia State Police web site; San Diego Police Department web site, Los Angeles police department web site, Dallas police web site, Detroit police department web site, Columbus division of police web site).

In an attempt to establish occupational vision standards, standards are often borrowed or “shared” between similar but not identical occupations. Space shuttle pilot astronauts who are responsible for shuttle operation, and mission specialist astronauts who have different responsibilities comprised of experimental and payload operations are both required to pass a NASA Class I space physical, which is similar to a pilot’s Class I flight physical (NASA HSF web site; NASA Astronaut Selection). In the past, Class I pilots were required to have “normal color vision”; this standard is still in place for all astronauts. However, all classes of pilots (1, 2 & 3) now have an amended color vision standard, which states they must have “the ability to perceive colors necessary for the safe performance of airman duties.” (DOT-FAA-14CFR Part 67).

An example of a vision standard that is based on a job-related color vision task is that of railroad engineers. The color vision standard is based on the ability to distinguish between red, green and yellow colored railroad signal lights, this being a railroad engineer’s primary color vision task (DOT-FRA-SA-98-1; DOT-FRA-49CFR240). Other occupational groups that require the ability to distinguish between colors versus having “normal” color vision are the non-deck officers within the Merchant Marines and commercial motor vehicle drivers (Berson *et al.*, 1998). Although there is no empirically supported color vision standard for the commercial motor vehicle industry, approximately 24% of the states have a color vision requirement for commercial motor vehicle drivers while the remaining states do not. (DOT-FMCSA-synthesis)

In addition to establishing vision standards, the FAA should outline the guidelines for testing of persons in order to detect visual impairments. In a Safety Advisory entitled “Determination of Vision Impairment among Locomotive Engineers” (DOT-FRA-SA-98-1) published by the Federal Railroad Administration (FRA) and the Department of Transportation (Paskiewicz, 2001), an example is provided of the importance of administering appropriate testing procedures. Although vision standards for railroad engineers had been established, the FRA’s expectation was that designated railroad medical examiners would administer appropriate color vision examinations. It was not anticipated that it would be necessary to specify the necessary testing procedures and materials to the medical examiners. This assumption has been called into question under tragic circumstances when an inappropriate color vision test prevented the detection of a significant color vision deficit, which led to a major railway accident involving a fatal collision between two New Jersey transit commuter trains (USDOT/FRA/SA-98-1). The



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NTSB report found that the suspect engineer's medical history showed that he had been administered an acceptable color vision test annually by the same contract physician for 9 years. In the tenth year, the test results showed a deterioration of the engineer's ability to distinguish among colors. The following year the engineer again demonstrated an inability to distinguish between certain colors and was evaluated with the Dvorine Nomenclature Test, a test of color naming ability and not color discrimination, to further evaluate his color vision. The engineer passed the test most likely because many color weak individuals can identify the names of colors by their brightness. The nomenclature test is a precursor to the Dvorine-Second edition test and is often skipped due to the assumption that most individuals know color names. The examiner failed to administer the accompanying Dvorine-Second edition color vision test, which is the color vision test that actually measures color discrimination abilities. It was ruled likely that the accident was preventable if the physician had used appropriate testing methods to measure the person's ability to distinguish colors (DOT-FRA-SA-98-1). To help prevent further testing mistakes and thus prevent possible accidents, specific guidelines should be provided in addition to the limiting visual requirement.

2.2 Visual Acuity

2.2.1 Relevant Terms and Basics

Visual acuity refers to a measure of spatial resolution of an individual's vision for a high contrast, static image. Near visual acuity refers to the acuteness or clarity of an image seen by the eye of an object that is approximately 13" away from the person being tested, middle visual acuity is measured when an object is between 13" and 3' from the person, and distance visual acuity is measured at approximately 20'.

When the eye is in focus, a sharp image is formed on the retina; visual acuity impairments result in the loss of sharpness of vision. Visual acuity measurements can be influenced by luminance, contrast, color, surrounding field size and intensity, time available to view an object, glare, refractive error, pupil size, attention, IQ, boredom, ability to interpret blurred images, emotional state, opacities of the cornea, lens or humors, and disease of the retina or optic nerve such as diabetic retinopathy, glaucoma or chorioretinitis (Riggs, 1965; Westheimer, 1987; Sturr *et al.*, 1990; Cornelissen *et al.*, 1995).

There are several types of acuity; the term visual acuity generally means resolution acuity, or the ability to discriminate two small points from a single point. Vernier acuity (Westheimer, 1975), another type of acuity of potential relevance to aircraft inspection, measures the eye's ability to discriminate the offset, or break, between two similarly oriented bars. This type of acuity would be useful for occupational tasks requiring line details, such as reading micrometers or precision gauges requiring the discrimination of a break in contour or alignment.

Distance visual acuity is often recorded as a fraction, with the numerator representing the testing distance, usually 20 feet or the equivalent, and the denominator representing the smallest line of letters the person being tested can see clearly. If an individual is able to read the 20/20 line of letters from 20 feet away, the letter image is subtending an angle of 5 minutes of arc. A score of 20/40 means that the smallest readable letters were twice this size; therefore, a 20/20 observer could have read the same letters from 40 feet. These



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values are usually recorded in feet, 20/20, or outside the United States in meters, 6/6. Near visual acuity can be recorded several ways, commonly it is recorded as a Snellen equivalent, and thus in the fraction form as described above. Near acuity may also be recorded as Jaeger acuity, a non-standardized system based on a printer's designation, or it may be recorded in metric notation, M. M units are the distance in meters that the lower case letter subtends 5 minutes of arc.

2.2.2 Visual Acuity: Real-world Performance Literature, Vision Standards, and Relevance to Aircraft Maintenance Inspection

Visual acuity has been the standard for evaluating vision for over 130 years. The acceptance of the Snellen chart in 1862 and the need to create military standards in 1913 provided the basis for the concept that "20/20" acuity is considered to be "good" vision. Visual acuity is often used as the primary indicator of an individual's visual health; however, it should be noted that an individual that can see 20/20 on a Snellen acuity chart could have an undetected ocular disease or condition that has not affected that person's central vision. Therefore, visual acuity measurements should be used as a measure of one specific visual ability and not extrapolated to represent the eye's overall state.

Several research groups have specifically studied the influence of visual acuity impairment on daily living. Szlyk *et al.* (2001) investigated the functioning in daily task performance of individuals with retinitis pigmentosa. The tasks were clustered into three categories: "reading," "mobility," and "peripheral detection." Moderate or significant difficulty in performance was observed only for visual acuity worse than 20/40; this corresponded to log contrast sensitivity of less than 1.4 and a visual field smaller than 50-degree in diameter. Haymes (2002) examined the relationship between clinical measures of vision impairment and the ability to perform activities of daily living. Distance visual acuity, near word acuity, contrast sensitivity and visual fields were measured on vision-impaired subjects. Results showed that all vision measures had a high, statistically significant correlation with performance score. Near visual acuity had the strongest correlation followed by contrast sensitivity. Kempen *et al.* (1994) found that visual acuity loss can result in low performance on facial recognition and form discrimination tasks such as reading letters. Thus clinical vision impairment measures can be highly correlated with capacity to perform daily tasks.

West *et al.* (2002) examined the association between performance on selected tasks of everyday life and impairment in visual acuity and contrast sensitivity. The results showed that both visual acuity and contrast sensitivity loss were associated with decrements in function. The relationship of function to the vision measures was predominantly linear; therefore, it is difficult to identify cutoff points for predicting disabilities. For heavily visually intensive tasks, such as reading, visual acuity worse than 20/30, or contrast sensitivity worse than 1.4 log units was disabling. Both contrast sensitivity and visual acuity loss contribute independently to deficits in performance on everyday tasks. Since cutoff points depend on the task, defining disability using a single threshold for visual acuity or contrast sensitivity loss is arbitrary.

The impact of visual acuity on job performance has been studied extensively. Parssinen *et al.* (1987) examined the need for visual acuity in daily work in different occupational groups. Their results show that there is a need for accurate vision in most occupations



and that the visual acuity and refractive error, or need for glasses, of the employees requiring accurate vision should be evaluated prior to beginning work.

It is estimated that 33% of the U.S. workforce have uncorrected, or insufficiently corrected, refractive errors that can affect task efficiency (Ungar, 1971). Workers over the age of 40 with presbyopia, an inability or decreased ability to focus on near objects, account for the majority of this statistic. These individuals require a near vision correction, reading glasses, or an addition of a near prescription to their present distance glasses prescription. An individual that has not needed glasses before the age of 40 usually needs glasses to improve their near vision after the age of 40; additionally their near prescription will need to be updated every few years as the near refractive error will continue to change over the years.

Visual acuity standards exist in many occupations where safety is imperative. (Appendix D) Visual acuity tests are the most prevalent vision test used to screen driver license applicants worldwide. Vision standards for the drivers of personal automobiles, commercial motor vehicle, and school bus drivers vary. Each state has established its own vision standards, which are imposed in order for an individual to obtain an unrestricted driver's license. These visual acuity requirements range from 20/40 to 20/100.

Higgins (1998) evaluated the effect of visual acuity degradation on different components of the driving task. Driving performance was measured while participants wore modified swimmer's goggles to which blurring lenses were affixed in amounts necessary to produce various decreased levels of visual acuity. Acuity degradation was found to produce significant decrements in road sign recognition and road hazard avoidance as well as leading to significantly slower overall driving time. Wood and Troutbeck (1994) also compared the driving performance of young, visually "normal" subjects under conditions of simulated visual impairment. Special goggles were designed to replicate the effects of cataracts, binocular visual field restriction, and monocular vision. Simulated cataract resulted in the greatest detriment to driving performance. Studies such as these have potential applications in defining empirically determined vision standards for driver license applicants and may also be applicable for determining vision standards for aviation NDI/NDT personnel.

Poor acuity cannot be consistently correlated to poor performance on visually demanding tasks. Although a few studies have reported a positive but weak association between visual acuity and automobile crash involvement (Ball & Owsley, 1991; Hofstetter, 1976; Marottoli, *et al.*, 1998); however, similar research has failed to provide evidence for decreased vision's role in traffic accidents (Burg, 1967, 1968). Possessing "good" visual acuity is not closely correlated to visual tasks such as seeing objects of different sizes and contrasts, whether visibility is clear or poor. Studies with pilots conducted in simulators and in field trials have shown that acuity alone is not an absolute indicator of actual task performance (Ginsburg *et al.*, 1982; Ginsburg, *et al.*, 1983). Regardless of these findings, visual acuity is still used as the primary indicator as to whether or not a person can see well enough to drive or pilot vehicles safely.

One specific study investigated the uncorrected distance visual acuity requirements for firefighters to perform "acceptably" (Padgett, 1989), and several studies have provided empirically determined uncorrected visual acuity standards recommendations for police



officers. (Appendix E) In these studies the vision standard was based on the specific visual needs of each specific occupation (Sheedy, 1980; Good & Augsburger, 1987; Good & Maisel, 1998). Although these recommendations exist, there is significant variability in the required vision standards between different police agencies throughout the United States (Holden, 1984) (Appendix F). Additional examples of occupations having variable visual acuity standards depending on the city or state in which an individual works are lifeguards and firefighters. (New York State Parks web site; Broward County, FL web page; Washington State Department of Personnel web site; U.S. Department of the Interior, 2002; Grand Junction, CO web site). The minimal uncorrected visual acuity requirement for military aircrew and air control personnel has been evaluated experimentally (Draeger & Schwartz, 1989). However, most aviation governing bodies, such as the FAA, no longer require a specific uncorrected visual acuity. At this time the FAA's best-corrected vision standards for all classes of pilots are similar to the International Civil Aviation Organization's (ICAO) vision standards; class I and II pilots are required to have at least one eye correctable to 20/20 at distance and 20/40 at near while class III pilots need at least one eye to be correctable to 20/40 at distance and 20/40 at near (DOT-FAA-14CFR). As with standards that have not been empirically derived, these standards appear to be based on expert opinion rather than job task analysis and empirical testing. Occasionally smaller individual industries, such as a basket manufacturing company, have taken the initiative and made arrangements for their own job-related vision standards to be empirically developed for their work force. (Ross, 1978)

Good *et al.* (1996) performed a systematic study on setting job-related vision standards for workers at a manufacturing plant. The study, as the authors claimed, can serve as a model for the application of visual standards to the workplace. In this study, the critical factors for performing specific visual tasks for 40 job classifications at a manufacturer of hand-woven baskets and accessories were identified. For each class of job, the study was carried out in four steps: 1) identifying the primary duty; 2) identifying specific visual tasks; 3) identifying specific visual requirements for VA, binocularity, color vision and visual field; and 4) assessing the level of visual performance necessary to accomplish the tasks and setting up the visual standards. Each class of job required sharp vision at near working distances. The research determined the level of near visual acuity necessary for each inspection task. In the experiments observers with "normal" vision performed inspection tasks under three viewing conditions: 1) normal viewing; 2) wearing lenses with a small amount of cylinder⁹ to decrease VA moderately and 3) while wearing a large amount of cylinder to decrease VA significantly. The altered near acuity was compared against each of the worker's performance errors, the resulting critical point of blur was determined to be 20/30. Above this acuity level the number of errors increased in a linear fashion. Therefore, the conclusion was that 20/30 near VA should be the standard for individuals' inspection tasks at this facility. More than 98% of the US population has at least 20/25 corrected VA; therefore, the 20/30 VA standard will not eliminate a significant number of workers from these jobs.

⁹ Cylinder or cylindrical lens: A lens whose refractive power varies from a maximum in one meridian to a minimum in the meridian which is 90 degrees away.



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Several industries without their own specific visual acuity standards have borrowed from other industry's standards; an example is the British electronics industry that uses the vision standards set forth by the American Society of Mechanical Engineers' (ASME) Code for Boiler and Pressure Vessels (Kennedy, 1989). The ASME's vision standards are for Nondestructive Examination, NDE, personnel involved in the inspection of nuclear power plant components (American Society for Mechanical Engineers, 2001). As stated earlier, some police departments have taken the initiative to empirically validate their visual acuity standards; however, there are other police and correctional departments that have instead applied the vision standards established by the National Fire Protection Association for firefighters, despite the dissimilarity of the various job tasks between these dissimilar occupations (MED-TOX Health Services).

There are many standards without clear empirical backing, including those for drivers of commercial motor vehicles (Federal Motor Carrier Safety Administration-49 CFR Part 391.41), Merchant Marines (U.S. Coast Guard: Marine Safety Manual III), welding inspectors (American Welding Society, 2002), and locomotive engineers (DOT-FRA 49CFR240). It is unclear as to the origin of the visual acuity standards for the Air Force and the Coast Guard, but their distance and near visual acuity standards are exactly the same, one likely having borrowed from the other; the near visual acuity standard is 20/40 while the distance visual acuity standard states that if the eye with better vision is correctable to only 20/40 the weaker eye must be correctable to at least 20/70, if the better eye is correctable to 20/30 then the weaker eye must be correctable to 20/100, and if the better eye is correctable to 20/20 the weaker eye must be correctable to 20/400. (USAF AFI 48-123; U.S. Coast Guard-DOT, 1988).

Finally, there are the industries that are interested in setting their own vision standards but that have not been able to empirically investigate the specific vision needs for their own work force, and they recognize that borrowed standards from other fields are not of use to them. An example industry is that of bridge inspectors (Glenn Washer, Director of NDE Center in McClain, VA, personal communication; DOT-FHA, 2001).

The detectability and discriminability of many airframe and engine defects may depend on the resolution of the human eye. Examples of tasks that are performed by the NDI inspector (and the typical inspection technique) that may require spatially acute visual abilities include:

- discriminate wear marks on a machine part (visual & borescope)
- small crack discrimination from other anomalies (visual, borescope, florescent penetrant)
- wiring frays (visual)
- reading computer screen (eddy current & ultrasonic)
- pitting, scoring, porosity, and tool marks (visual & borescope)
- fit of seals, bonds, gaskets, and sub-assemblies in difficult to reach areas (visual & borescope)
- assess Foreign Object Damage (FOD) in aircraft, airframe, and power plants (visual & borescope)



- paint chips (visual)
- cracks, nicks, missing material (visual)

Essentially all the aircraft inspection work described above requires an inspector to search for fine flaws in materials; thus, sharp visual acuity at near as well as middle distances may be needed.

Grundy (1997) proposed a general task analysis method for specifying visual acuity standards. The methods included: 1) determining the working distances involved and the size of visual details; 2) using a nomogram to determine the minimal visual acuity for the task and 3) setting a visual acuity standard at approximately twice the minimum level. With many tasks the viewing distances and the flaw sizes are difficult to determine, such as the tasks involved in aircraft inspection; thus, elaborated visual experiments are needed to help determine appropriate aviation maintenance visual acuity standard.

When setting visual acuity standards, as with any other visual standards, the purpose of the qualifying test must be defined, the medical personnel performing the evaluation should have detailed testing protocol available, and the pass/fail criteria should be unambiguous.

2.3 Visual Fields

2.3.1 Relevant Terms and Basics

The “normal” visual field for an individual with binocular vision extends approximately 190 degree horizontally and 120 degree vertically (Weston 1962). Sensitivity to a stationary visual stimulus is greatest in the area of the retina referred to as the fovea; this area corresponds to the central visual field and is approximately 4 degrees in size. The parafoveal area, which surrounds the true foveal area, is 5-10 degrees in size. The remaining field area is referred to as the peripheral field. Humans rely on foveal vision for reading and object recognition, (Latham and Whitaker, 1996) while peripheral vision is essential for sensing movement, searching for targets, and maintaining orientation. Color discrimination, contrast sensitivity, and acuity are markedly worse with increasing eccentricity from the fovea (Martin *et al.*, 2001; Rovamo, 1983). Contrast sensitivity declines can be attributed to a reduced cortical representation with eccentricity (Rovamo, 1983), while color vision deterioration has been attributed to reduced color specificity in peripheral retinal cells (Martin *et al.*, 2001).

Individuals with peripheral vision loss are often capable of retaining clear central vision. In some cases small patches of retinal activity in the periphery are preserved; thus making it possible to detect movement, and objects that may assist with one's orientation.

Disease or age-related visual field restrictions are not the only parameters that can limit the aircraft maintenance inspectors' peripheral vision. Pyramid-type task analysis has revealed that the borescopes can limit the inspector's field of view, removing beneficial landmarks (Drury, 2001). In addition, spectacle frames and opaque side shields on safety spectacles can restrict the visual field. Age influences the extent of the useful visual field dramatically. The incidence of visual field loss is 3.0% to 3.5% for persons aged 16 to 60 years but is approximately 13.0% for those older than 65 years (Johnson



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and Keltner 1983). The lateral visual field begins to decline at the average age of 35 years (Burg 1968; Ball, Beard, Roenker, Miller, Griggs, 1988). The most common causes of visual field loss are glaucoma, retinal disorders, and cataract.

2.3.2 Visual Fields: Real-world Performance Literature and Relevance to Aircraft Maintenance Inspection

Alfano and Michel (1990) examined the role of peripheral vision in visuomotor activities such as walking, reaching, and forming a cognitive map of a complex field. They used goggles that limited the field of view to 9 degrees, 14 degrees, 22 degrees, or 60 degrees. Each restriction of peripheral field resulted in perceptual and performance decrements. The 9 and 14-degree restrictions produced the greatest disturbance, especially in forming a cognitive map that is important for visual search. Visual search in industrial inspection has been widely studied since the 1960's Badalamente & Ayoub (1969). As summarized by Schoonard and Gould (1973), inspectors must simultaneously and rapidly look for multiple defect types.

Efficient visual search is characterized as systematically scanning a field of fixed size. Hockberg (1978) and other researchers have suggested that peripheral vision guides the scanning field to the potential target site where the features can then be scrutinized. To study the relationship between search performance and visual field size, Kundel *et al.* (1991) used a system called the eye-position interactive display, in which subjects searched for lung nodules within photographic chest x-ray images. The eye-position interactive display positions the nodule within a specific part of the visual field without disturbing the chest image appearance. It was found that the time required to scan the image and fixate a nodule was shortest for nodules that were both reported and accessible to peripheral vision. A stepwise concentric reduction in the peripheral field size only affected search performance when the field size was less than 5 degrees. These data support the hypothesis that the optimal scanning strategy for lung nodules consists of spacing fixation clusters 5 degrees apart, and that the peripheral field beyond 5 degrees adds little to the discovery of nodules in a systematic search process. Peripheral vision guides the gaze to inconspicuous nodules and accelerates the discovery of some nodules.

Melloy *et al.* (2000) developed a model that characterized the trade-off between the search speed and accuracy in aircraft inspection. The accuracy depends on the number of fixations, the probability of detection, and the search field size. With a restricted field of view, the number of fixation would increase accordingly in order to cover the same size field being searched. This in turn would decrease the accuracy of visual inspection. Many studies on visual search in inspection have been devoted to improving search strategies (Wang *et al.*, 1997; Megaw and Richardson 1979; Tsao *et al.*, 1979; Gramopadhye *et al.*, 1997). These studies show that the most useful search strategies include systematic search and expanding the useful field of vision, UFOV. Few studies have tried to quantify the optimal visual field size required for those search strategies.

A great deal of research has been done on vehicular driving performance with normal and abnormal visual fields. Johnson and Keltner (1983) performed visual field screening of 10,000 volunteers, finding that drivers with binocular visual field loss had accident and conviction rates twice as high as those with normal visual fields. Wood and Troutbeck (1994) simulated restricted vision using goggles designed to replicate the effects of cataracts, binocular visual field restriction, and monocular vision. Simulated cataract



resulted in the greatest detriment to driving performance in a simulator, followed by binocular visual field restriction. Schiefer *et al.* (2000) studied the influence of typical visual field defects, such as scotomas, on visual perception. The results demonstrated that the evaluation of the borders of visual field size alone were not sufficient for determining driving fitness.

Recent studies have found that current clinical screening tests of visual fields (perimetry testes) are not satisfactory predictors of driving performance (Myers *et al.*, 2000). Schulte *et al.* (1999) found no differences in driving performance (driving speed, reaction time, and driving error rate) between subjects with normal and defective visual fields, as measured with classic perimetry tests. In occupational studies researchers often prefer the measurement of the "useful field of view" (UFOV) to the conventional measurement of the visual field, which generally corresponds to a measure of boundary size and seldom provides information pertaining to the overall field within the boundary. The UFOV task, developed by Ball and colleagues (Ball, Beard, Roenker, Miller, and Griggs, 1988; Ball, Owsley & Beard, 1990) relies on higher-order skills, such as selective and divided attention and rapid visual processing speed. Several studies have shown that drivers with the most severe restrictions in their UFOV tend to have the highest number of crash involvements (Ball & Owsley, 1991; Owsley *et al.*, 1998; Owsley & McGwin, 1999) and that the addition of screening tests beyond UFOV alone do not increase predictive validity (Myers *et al.*, 2000). Aviation maintenance inspectors often need to be able to attend to several areas of an aircraft at once while searching for targets of importance and discriminating them from the remaining visual scene. UFOV methodology may help determine whether aircraft maintenance inspectors need parafoveal or peripheral vision to adequately perform these duties. Tasks requiring divided attention correlate better to UFOV measures than they do to classical clinical perimetry measurements (Ball, Owsley & Beard, 1990).

In general there is a lack of sited empirical research to support most occupational visual field requirements. Air traffic controllers in terminal and center positions must have both "normal" central and peripheral visual fields. They are required to have 140-degree fields in the horizontal meridian and 100 degree fields in the vertical meridian (U.S. Office of Personnel Management, 2001). The U. S. coast guard's standards leave nothing to interpretation, their visual field standards are specific in eight separate meridians, i.e. superior, superior nasal, nasal and so forth. The temporal meridian, measured from straight ahead outward toward the ear, for each eye is 85 degrees; therefore, together the binocular horizontal visual field requirement is 170 degrees for coast guard applicants (Coast Guard Medical Manual). Other occupations with specified field size requirements include merchant marines, wildland firefighters and railroad engineers.

Empirical research has been conducted to determine visual field requirements for correctional officers. The suggested standard includes the need for two functioning eyes and an associated full visual field of no less than 120 degrees in order to prevent a decrease in acceptable job performance when supervising inmates in the same room or area (MED-TOX Health Services).

Visual field standards are occasionally borrowed from one occupation to be used by another. The visual field standard for forklift operators at one company came from the Federal Department of Transportation's standard for commercial drivers (Ross, 1978).



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Commercial motor vehicle drivers are required to have 70 degree visual fields in the horizontal meridian for both the right and left eyes, this equals a 140 degree binocular field (Federal Motor Carrier Safety Administration 49 CFR Part 391.41; Berson *et al.*, 1998; Ross, 1978). The majority of states in the U.S. do not have a visual field requirement for private motor vehicle drivers and of the approximately 15 states that do, the horizontal visual field size requirement ranges from 100 to 140 degrees (North, 1985).

Not all occupational visual field standards are specified as a numeric value, although the qualifying designation of “normal” gives no explanation as to what size or shape constitutes a “normal” field. Examples of Federal occupations with the requirement of "normal" visual fields includes border patrol agents, customs patrol agents, mining safety inspectors, nuclear materials couriers, and criminal investigators, while federal occupations with visual acuity standards but no visual field requirements include U.S. Marshals, correctional officers, security guards, and food inspectors (U.S. Office of Personnel Management, 2001).

As with previously mentioned visual parameters, occupational visual field requirements should include specific visual field size measurements and acceptable testing procedures for both the central and peripheral fields.

2.4 Contrast Perception

2.4.1 Relevant Terms and Basics

Practically speaking contrast sensitivity is a measure of the limit of visibility for low contrast patterns -- how faded or washed out can images be before they become indistinguishable from a uniform field? Only with sufficient contrast do objects become distinct enough from the background as to be detectable. Contrast sensitivity is typically plotted as a function of the size (coarse/fineness) of an image's features, or the spatial frequency. This plot is called the contrast sensitivity function (CSF). The test image shown below was first produced by Campbell and Robson (1968) to illustrate the form of the function in a very intuitive manner -- using everyone's own visual system and without time-consuming measurements.

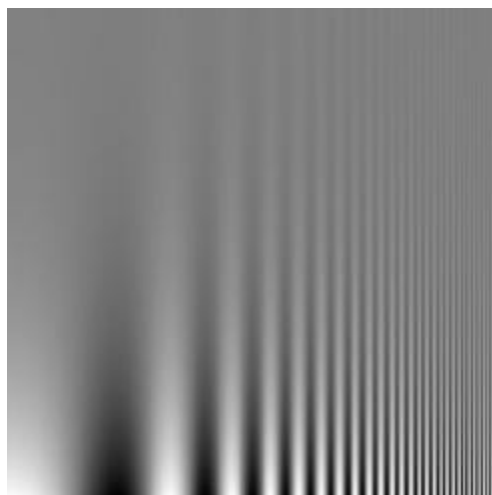


Figure 3. Contrast sensitivity demonstration.



Contrast sensitivity can be measured clinically using gratings, light and dark striped targets. Charts used to measure contrast sensitivity use these various grating targets to display patterns at variable spatial frequencies and contrasts. As the frequency of the stripes increases, or the closer the stripes are to one another, the contrast between the stripes will decrease (Moriarty & Hitchings, 1988).

2.4.2 Contrast Sensitivity: Real-world Performance Literature and Relevance to Aircraft Maintenance Inspection

Compared to Snellen visual acuity measurements, the contrast sensitivity has emerged after over the past 30 years of scientific testing as a more comprehensive technique of describing vision (Proenza *et al.*, 1981; Committee on Vision, National Research Council, 1985). In Section 2.3 visual acuity was described as a measure of the smallest detail that the visual system can resolve. When assessing visual acuity, one is interested only in the spatial (size) factors that limit vision; therefore, additional separate factors, such as contrast, are optimized during testing. When an eye chart is printed with light gray ink on a gray card stock, rather than with the standard black ink on white card stock, the letters are harder to see (Regan, 1988). The letters' reduced contrast limits visual acuity, suggesting that performance cannot be assessed based on size alone. Measures of the CSF are informative as to how both image contrast and size limit vision. Contrast sensitivity test charts have provided a simple method by which to measure threshold levels and have been used for almost 20 years in clinical and performance trials (Evans & Ginsburg, 1985).

CSF measurements are highly correlated with a patient's perceived visual disability, particularly their subjective assessment of the effect of vision on their mobility-orientation (Elliott, Hurst, & Weatherill, 1990). Two people with exactly the same visual acuity can have significantly different contrast sensitivity functions. Many instances in which contrast sensitivity loss was detected when visual acuity was normal have been reported. Although impairments in visual acuity are reflected in measures of contrast sensitivity (Marmor & Gawande, 1988), experiments have shown that visual acuity and contrast sensitivity measurements cannot predict each other on one measurement alone (Peregrin *et al.*, 1992).

Population data has been obtained for visual acuity and contrast sensitivity (Grimson *et al.*, 2002; Haymes *et al.*, 2002; West *et al.*, 2002) and related to real world performance. A strong relationship between high spatial frequency contrast sensitivity loss and visual acuity with self-reports on driving difficulty was shown in 288 drivers over the age of 55 with cataract compared to a control group of 96 drivers with no indication of cataract (McGwin *et al.*, 2000). A separate study from the United Kingdom showed that automobile crash involvement increased for drivers with below average low contrast visual acuity (Slade *et al.*, 2002). In Canada, it has been acknowledged that reduced contrast sensitivity can affect driving ability in spite of the driver having "adequate" visual acuity; additionally, they recommended that further research is needed to understand what level of reduced contrast sensitivity represents an unacceptable driving risk (Canadian Ophthalmological Society, 2000).



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Significant visual acuity and contrast sensitivity loss do not necessarily negatively affect mobility in the environment, but a decrease in either may affect more visually intensive tasks such as the ability to read - visual acuity worse than 0.2 logMAR (20/30) or contrast sensitivity worse than 1.4 log units was disabling (West *et al.*, 2002). Decreased measurements in acuity, contrast sensitivity, and UFOV were independently associated with longer times to complete everyday tasks such as reading ingredients on cans of food, reading instructions on medicine bottles, finding a phone number in a directory, or locating items on a crowded shelf and in a drawer (Owsley et al., 2001).

Contrast sensitivity testing often provides early detection of serious eye diseases that a standard letter acuity chart may not detect until the condition is more advanced. When contrast sensitivity values are below “normal” for an individual’s age, they have helped in the detection of diseases and/or conditions commonly associated with decreased contrast sensitivity such as cataracts, glaucoma, amblyopia, macular degeneration, keratoconus, and optic neuritis.

The following is a list of airframe or powerplant defects whose detection may potentially rely on contrast perception.

- cracks
- corrosion (visual & borescope)
- weld joints
- solder connections
- adhesive disbonds
- identifying water or skin bulges (X-ray)
- reading computer screen (eddy current & ultrasonic)
- pitting, scoring, porosity, and tool marks (visual & borescope)
- fit of seals, bonds, gaskets, and sub-assemblies in difficult to reach areas (visual & borescope)
- assess Foreign Object Damage (FOD) (visual & borescope)
- rippling on airframe indicating subcutaneous corrosion
- seams, voids, pits
- other surface, or subsurface, discontinuities in ferro-magnetic materials

Based on our observations of crack and corrosion detection thus far, contrast perception is a critical visual process in NDI inspection. An example is of aluminum or magnesium corrosion, which appears as a white or gray powder against a painted surface. In order to detect this powder, adequate perception of contrast is a likely requirement. Further research is needed to confirm this contention.

A common way for inspectors to increase surface crack detectability is to shine their flashlights at a 5 to 45-degree angle relative to the aircraft surface (AC 43-204). In visual psychophysical terminology, they have increased the object’s detectability using “shape from shading” cues (Cavanagh & Leclerc, 1989). These shadows can accentuate the



depth and form of objects, improving visibility.

In the past, a few military standards documents such as MIL-STD-271 have addressed contrast sensitivity requirements. This document advised that radiographic personnel be tested for brightness discrimination, but no guidelines were given as to the desired standard or testing procedure (Kleven & Hyvärined, 1999). The most up to date document that supersedes MIL-STD-271, NAVSEA T9074-AS-GIB-010/271, does not mention a brightness discrimination or contrast sensitivity standard.

We were unable to locate current contrast sensitivity standards in industry or the military; however, contrast sensitivity is being considered as a future tool for evaluating visual requirements of aircraft pilots, especially in those individuals with borderline visual acuity that may prevent their selection into pilot training programs (Gray, 1985). Presently data is being gathered from within the military aviation community in order to establish normative contrast sensitivity values. In the future these data may be used to set up contrast sensitivity standards for commercial and general aviation pilots.

Contrast sensitivity is not traditionally included in occupational vision standards. Although high contrast acuity is undoubtedly important for some everyday tasks, natural scenes are predominantly composed of low contrast information (Brady & Field, 2000). Contrast sensitivity has been found to be a better predictor of target detection and recognition than standard visual acuity measures for pilot's attempting to detect ground-to-air targets in field studies (Ginsburg *et al.*, 1983) and in simulators (Ginsburg *et al.*, 1982), for detection and discrimination of faces (Beard & Ginsburg, 1991), for military tank detection in outdoor scenes (Rohaly *et al.*, 1997) and for simulated aircraft on a runway (Ahumada & Beard, 1997a,b). Thus, measuring the ability to see low contrast images may be worth considering when determining vision standards and tests for individuals needing to see small objects at low contrast levels (Kleven & Hyvärined, 1999).

2.5 Depth Perception

2.5.1 Relevant Terms and Basics

With binocular vision (two eyes), the impression of spatial depth is enhanced as compared to monocular (one eye) vision. Due to each eye being located at different positions in the skull, each eye's retina receives a slightly different view of an object from that of the other eye. This leads to the perception of depth when the images are combined in the brain. The discrepancy between images and thus the perception of depth is greater the closer the object being viewed is to the observer. Based on this, the implication for aircraft maintenance inspection may be that inspectors should have normal binocular vision. However, a monocular individual has the ability to use various cues to determine an object's distance from the observer: such as object size differences, amount of overlap of multiple objects, and motion parallax or a slight shifting of the head to achieve a certain degree of depth perception. At this time it is unknown as to whether monocular vision is adequate when performing inspection tasks.



2.5.2 Perception of Depth: Real-world Performance Literature and Relevance to Aircraft Maintenance Inspection

If an aircraft maintenance inspector's two eyes do not work together, his perception of aircraft components may be compromised. Advisory circular 43-204 (1997) states that one of the fundamental elements of successful visual inspection is for a trained inspector to have binocular vision and good visual acuity.

Using stereo photographs of real objects, Doorschot, Kappers, & Koenderink (2001) varied the position of a light source to obtain different shape from shading cues. They found that surface attitude settings were based on both these shading cues as well as binocular disparity cues.

Few occupations have binocular vision requirements and even fewer have conducted research to verify their specific binocular vision standards. One paper was found describing a company that contracted to have appropriate vision standards devised for its various job positions. An initial recommendation was made that forklift operators have 80" of stereoacuity. This recommendation was based on observations made of workers during normal forklift operations and while one of their eyes was occluded during forklift operations. Upon screening the vision of these same forklift operators it was found that 20% of the forklift operators did not meet the standard. However, their safety record was devoid of accidents causing injury or product damage. This non-empirically determined standard was removed due to the safety record and the workers' ability to perform acceptably even without "good" stereoacuity (Good *et al.*, 1996).

A few binocular vision standards are stated in terms of the eyes' muscular balance and the eyes' ability to work together, verses a specific numeric binocular acuity value as described before. For instance the Department of the Navy does not have a depth perception requirement for aircrew maintenance personnel, but they do require that individuals have no "obvious heterotropia (eye turn) or symptomatic heterophoria (poor bi-ocular alignment)" (Department of the Navy, Bureau of Medicine and Surgery, 1996). Years ago Air Traffic Controllers had a stereoacuity standard that is no longer in place. Presently the requirement for phorias for Air Traffic Controllers in terminal and center positions states that if they have a horizontal phoria that measures greater than 10 prism diopters in either horizontal direction or a vertical phoria that is greater than 1 1/2 prism diopters they must be evaluated by an eye specialist to establish that they meet the broader requirements of bifoveal fixation and that the two eyes work together (U.S. Office of Personnel Management, 2001). The standards for a first-class airman's medical certificate are similar in that they require bifoveal fixation which must be determined if an individual is found to have more than 1 prism diopter of hyperphoria or 6 prism diopters of esophoria or exophoria, the horizontal phorias (DOT-FAA-14CFR). The standards for the U. S. Coast Guard simply state that there shall be "no strabismus (eye turn) or diplopia (double vision)" (Coast Guard Medical Manual).

As with visual field standards, many occupations state that binocular vision needs to be "normal" without giving guidelines as to what degree of ocular alignment or stereoacuity constitutes "normal". Examples of occupations having visual acuity standards in addition to the standard of "normal" binocular vision within the Federal Government include U.S. Marshals, nuclear materials couriers, wildland firefighters, criminal investigators, and mine safety personnel. Examples of those without any standard include border and



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customs patrol officers, corrections officers, security guards, pharmacists and dental officers (U.S. Office of Personnel Management, 2001). Also within the Federal Government is the occupation of food inspector with an even less specific binocular vision requirement of "clear and accurate depth perception".

It is not only unclear as to how the above-mentioned standards were chosen, but there are no outlined specifications as to which binocular vision testing procedures are clinically acceptable when testing for these standards. Due to this and the fact that none of the occupations having binocular vision standards are similar to those of aviation maintenance inspectors, these standards should not be adopted as standards to qualify an aviation maintenance inspector's vision.

3.0 Discussion

Although non-destructive testing does not ensure that aircraft components will not fail, it does provide a significant safeguard against such failures. Vision provides a valuable non-destructive testing approach. It is therefore imperative that aircraft maintenance inspectors possess universally acceptable visual abilities. It is difficult, if not impossible, to eliminate human error in the process of inspection; therefore, interventions must be developed to reduce errors and make the process more error-tolerant. One error mitigation strategy being pursued by the FAA is to standardize the vision requirements for the maintenance inspection industry.

Vision standards have been written for many occupations including correctional officers, firefighters, pilots, welders, automobile drivers, and astronauts. Typically, optometrists or ophthalmologists provide expert opinions when visual requirements are established for a particular occupation. Seldom have occupational vision standards been empirically derived. Individual occupations elicit unique visual demands upon their workers and thus require different visual skills; therefore, standards for specific job classifications should be based on each occupation's task specific vision requirements.

For many occupations, recruitment, testing, and training costs are high, and thus the rejection of qualified employees imposes an unnecessary expense on businesses, including aviation maintenance facilities. While the failure to properly perform certain maintenance related visual tasks could be catastrophic, persons with correctable visual limitations, who can perform their job, should be permitted to do so. Vision requirements should be based on a demonstration that, for example, 20/25 near or 20/50 distance visual acuity is actually needed to perform essential tasks. In addition, vision requirements should be based on tasks that cannot be modified by currently available technology that would assist the worker's vision.

Tasks performed by a licensed aircraft mechanics and inspectors change over time due to advances made in technology; such as, advances in computer technology, solid-state electronics, and improvements in structural material. Thus, there is an associated need to develop a task-based methodology that will permit fast, representative determinations of visual requirements with respect to all acceptably used technologies.

There are many variations of vision loss; therefore, knowledge about the type and extent of the loss is required to definitively determine whether an inspector should be excluded from performing specific individual tasks, or dismissed from their job completely.



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Research is needed to identify the degree and range of vision weakness that is acceptable for NDI inspection of aircraft.

In 1998 a major study was conducted by the Federal Highway Administration to determine if the visual inspection of bridges was accurate and reliable (Glenn Washer, Director of NDE Center in McClain, VA, personal communication; DOT-FHA, 2001). The study involved the collection of performance data including results from inspections, inspector' characteristics, and the inspection environment. Based on the results of this study, it was recommended that research be performed to determine if vision standards would have a significant impact on the inspection process. Similarly, it is not known if standardizing the vision requirements for maintenance inspection will have a significant impact on their performance. NASA Ames Research Center has proposed a methodology that will permit such a determination (Beard *et al.*, 2002). Through systematic simulation of typical visual defects, such as blurred vision, color vision loss, contrast sensitivity loss, and visual field defects, the effects of such defects can be assessed. In addition, these data can be used to define the range of acceptable deficits that can still exist without effecting performance.

Is there sufficient information in the published literature to write a vision standard for aircraft maintenance inspection? Currently, each airline or aircraft maintenance facility determines their own vision standards for their maintenance inspectors based on various NDI/NDT standards recommendations. In trying to make these standards more universal throughout the aviation maintenance community the need arises to determine if an empirical evaluation of the necessary visual requirements has been carried out for a similar occupation so that all or part of those standards can be used in the aviation maintenance industry. Based upon our literature review of occupations that have empirical justification for their standards, none of the job requirements are similar to those of an aviation maintenance inspector; therefore, their standards do not lend themselves to being borrowed by the aircraft maintenance inspection industry. Several occupations have empirically determined all or a portion of their vision standards; of those, pilots, air traffic controllers, mariners, police and firefighters all have various job specific tasks which do not overlap with those of an aviation maintenance inspector. It would be unacceptable to borrow vision standards from any of these occupations due to the extreme differences between each of their visual tasks and the tasks of aviation maintenance inspectors. Of the occupations that have similar job tasks, none have empirically backed vision standards.

In conclusion, our review revealed no studies or other evaluations that supported or explained the origin of any of the present NDI vision standards, nor is any literature available to substantiate the borrowing of vision standards from other occupations. Vision standard developed for aviation maintenance inspectors must take into account their own specialized inspection tasks and the environments in which they work.



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Appendix A

Recent Standards Documents with Vision Requirements

ATA 105	Air Transport Association	2002
Guidelines for Training and Qualifying Personnel in Nondestructive Testing Methods		
NAS 410	Aerospace Industries Association	June 2002
NAS Certification & Qualification of Nondestructive Test Personnel		
PSL/44	British Institute of Non-Destructive Testing	March 5, 2002
Vision Requirements		
AC 65-31	Federal Aviation Administration	October 1, 2001
Training, Qualification, and Certification of Nondestructive Inspection (NDI) Personnel		
AWS D1.1/D1.1M:2002	American Welding Society	August 31, 2001
Inspector Qualification Requirements		
ASNT CP-189-2001	American Society for Nondestructive Testing	July 30, 2001
ASNT Standard for Qualification and Certification of Nondestructive Testing Personnel		
ASME IMA-2300	The American Society of Mechanical Engineers	July 1, 2001
Qualifications of Nondestructive Examination Personnel		
SNT-TC-1A 2001	American Society for Nondestructive Testing	May 2001
Recommended Practice No. SNT-TC-1A 2001		
ISO 9712:1999	International Organization for Standardization	1999
Non-destructive testing – Qualification and certification of personnel		
NAVSEA T9074-AS-GIB-010/271	Department of the Navy	1999
Requirements for Nondestructive Testing Methods		



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AS7114

Society of Automotive Engineers

1997

National Aerospace and Defense Contractors Accreditation Program Requirements for
Nondestructive Testing



Appendix B

Visual Acuity Standards and Required Testing Frequency

	NEAR Visual Acuity	DISTANCE Visual Acuity	FREQUENCY Of Testing
ATA 105 Air Transport Association	20 / 25	20 / 50	≤ 2 years
NAS 410 Aerospace Industries Association	Jaeger 1	---	≤ annually
PSL/44 British Institute of Non-Destructive Testing	Jaeger 1	---	≤ annually
AC 65-31 Federal Aviation Administration	20 / 20	---	≤ annually
AWS D1.1/D1.1M:2002 American Welding Society	---	20 / 40	≤ annually
SNT-TC-1A American Society for Nondestructive Testing	Jaeger 2	---	annually
ASNT CP-189-2001 American Society for Nondestructive Testing	Jaeger 1	---	≤ annually
ASME IMA-2300 The American Society of Mechanical Engineers	20 / 25	20 / 30	≤ annually
ISO 9712:1999 International Organization for Standardization	Jaeger 1	---	<u>annually</u>
NAVSEA T9074-AS-GIB-010/271 Department of Navy	Jaeger 1	---	≤ annually
AS7114 Society of Automotive Engineers	Jaeger 1	---	annually
A Major Airline			



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	20 / 20	20 / 25	≤ 2 years
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Appendix C

Color Vision Standards and Required Testing Frequency

	COLOR VISION REQUIRED	FREQUENCY Of Testing
ATA 105 Air Transport Association	YES	≤ 3 years
NAS 410 Aerospace Industries Association	YES	Initially & recertification
PSL/44 British Institute of Non-Destructive Testing	YES	Annually
AC 65-31 Federal Aviation Administration	YES	At initial qualification
AWS D1.1/D1.1M:2002 American Welding Society	NO	---
SNT-TC-1A 2001 American Society for Nondestructive Testing	YES	Initially & every 3 years
ASNT CP-189-2001 American Society for Nondestructive Testing	YES	Initially & recertification
ASME IMA-2300 The American Society of Mechanical Engineers	YES	Annually
ISO 9712:1999 International Organization for Standardization	YES	Annually
NAVSEA T9074-AS-GIB-010/271 Department of Navy	YES	During initial qualification
AS7114 Society of Automotive Engineers	YES	Certification & recertification



A Major Airline	YES	Once during employment
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Appendix D

Various Visual Acuity Requirements for Occupations within the Federal Government

	VA-corrected	VA-uncorrected
U.S. Secret Service	20/20 x 2	20/60 x 2
Nuclear Mat. Courier	20/20 x 2	20/70 x 2
Border Patrol Agent	20/20 x 2	20/70 x 2 & 20/40 (bi)
Customs Officer	20/20 x 2	20/200 x 2 & 20/40 (bi)
U. S. Marshal	20/20 (binoc)	20/200 x 2
Bureau of Alc. Tobac. Firearms	20/20 & 20/30	20/100 x 2
Surface Mine Reclamation	20/30 & 20/50	20/200 x 2
Mine Safety & Health	20/30 & 20/50	20/50 & 20/70
Firefighter	20/30 & 20/70	20/100 (no SCL)
Forestry	20/20 & 20/30	---
Corrections Officer	20/30	---
Corrections Admin.	“usable vision”	---
Security Guard	“good vision”	---
Agriculture Warehouse Examiner	“good in one eye”	---
Dental Officer	---	---
Pharmacist	---	---



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Appendix E

Empirically Derived Vision Standards

<p>Air Traffic Controller:</p> <ul style="list-style-type: none">• Identify aircraft and their direction of flight at night and in daytime• Identify the color of the Aviation Signal Light indicator• Read color weather radar displays <p>Color vision = Normal Mertens: 1990,'92,'96</p>
<p>Firefighter:</p> <ul style="list-style-type: none">• Spot people at distance ≥ 20 ft.• Read codes on tankers <p>Uncorrected Distance VA = 20/100 Padgett: 1989</p>
<p>Police Officer:</p> <ul style="list-style-type: none">• Identify a weapon at 20 feet <p>Uncorrected Distance VA = 20/125 Good: 1998 Uncorrected Distance VA = 20/45 Good: 1987</p>
<p>Industry: Basket Manufacturing Good: 1996</p> <p>Slicer Operator:</p> <ul style="list-style-type: none">• Inspect materials for imperfections• Monitor slicer output <p>Corrected Distance VA = 20/40 Corrected Near VA = 20/30</p> <p>Dye Technician:</p> <ul style="list-style-type: none">• Inspect materials for gross imperfections and color correctness• Dye materials <p>Corrected Near VA = 20/40</p>



Warehouse Worker:

- Operate fork lift
- Read codes, inventory sheets and order requests

Corrected Distance VA = 20/50

Corrected Near VA = 20/40

Appendix F

	Los Angeles standards	San Diego standards	Dallas standards	Detroit standards	Columbus, OH standards	Sheedy 1980 recommended	Good 1998 recommended
Distance Visual Acuity Corrected	---	20/20	20/20 for each eye	20/20 for each eye	20/20 for each eye	20/20 binocularly	
Distance Visual Acuity Uncorrected	20/40 (with CL: none)	20/70 (with CL: none)	20/100	---	20/125 binocularly	20/40 binocularly	20/125
Color Vision	“name”	“acceptable”	“normal”	“normal”	---	“normal or anomalous trichromacy”	
Depth Perception	---	“normal fusion”	---	“normal”	---	<u>Stereoacuity:</u> ≥ 80”	
Visual Field	---	“normal”	---	---	---	“normal”	

Various Police Vision Standards and Recommended Vision Standards